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ACTDesal: A System Dynamics Model in Conversation
A systemic assessment of Cape Town's Opportunities in Water Augmentation

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Abstract

Within Cape Town, weather variability has led to a 3-year failure to meet the set yield requirements by the government – resulting in a serious drought, whereas dam levels have been pushed to as little as 18% of their total capacity in May 2018 (GreenCape, 2018). With enhancement of water demand management programs, the government has prevented the dams to reach a critical point called 'Day Zero' – the day the taps in the city are portrayed as 'running dry'. In this scenario, the reticulation network will be severely restricted with residents constrained to a daily ration of 25 liters of drinking water/person/ day. As water demands continue to grow and dams within the Cape region are almost reaching their limit capacity, Cape Town is one of the South African coastal cities that are considering augmentation programs as a potential future water supply source. This research attempts to map the entire water supply and demand system in the City of Cape Town and subsequently chooses to focus on desalination as this is different to more conventional surface and groundwater supply sources as the method is completely climate-resilient, thus obtaining an assurance of supply of essentially 100 percent. However, the increased reliability comes at a cost. In an attempt to ensure sustainable development, this research explores the multiple costs and benefits in their interdependent forms of water supply systems, regarding financial costs of desalination, possible socio-economic impacts thereof and the implication on the environment. This research explores the implications and dynamics of adding desalination to the City of Cape Town's water supply mix in terms of associated financial, socio-economic and environmental impacts, both positive and negative. The action research project in conversation with stakeholders uses System Dynamics modelling (SD) – which is a form of systems analysis – to assess the city's short- and long-term desalination strategies and plans in order to develop an interactive decision support system that is useful to both technical and non-technical stakeholders in Cape Town. The research contributed vastly to the mental models of the stakeholders, showing the balancing effect of higher water pricing through desalination, the impact on the pelagic fish species in either the Benguela or Aguillas current together with its subsequent costs and the financial costs of the proposed desalination.

List of abbreviations

ABBREVIATION	EXPLANATION
ACTDESAL	Assessment of Cape Town Desalination
ACTWATER	Assessment of Cape Town Water
ATL	Atlantis Aquifer
ACDI	African Climate & Development Initiative
CAPEX	Capital Costs
CCT	City of Cape Town
CESR	Committee of European Securities Regulators
CFA	Cape Flats Aquifer
CLD	Causal Loop Diagram
CTWRP	Cape Town Water Resilience Plan
DWA	Department of Water Affairs
DWS	Department of Water and Sanitation
EIA	Environmental Impact Assessment
FAO	Food and Agriculture Organization
IDA	International Desalination Association
ML	Megaliters
MM	Mediated Modelling
NGO	Non-Governmental Organization
OPEX	Operational Costs
PM	Participatory Modelling
PUB	Public Utilities Board
RO	Reverse osmosis
SD	System Dynamics
SUWI	Stellenbosch University Water Institute
TMG	Table Mountain Group Aquifer
UCT	University of Cape Town
UN	United Nations
URV	Unit Reference Value
WC/WDM	Western Cape Water Demand Management plan
WC/WSM	Western Cape Water Supply Management plan
WC/WSS	Western Cape Water Supply System

1. Introduction

1.1 The Water Crisis

Water is a natural resource which is required for the survival and development of humanity. It is one of the four basic elements constructing the environment we live in and is an important resource in the maintenance of human civilization and social progress. Over the last three decades, it has become increasingly difficult to ensure global water security. As of today, we are much more reliant on fresh water to keep up food production for a fast-growing population. By 2050, it is projected that the world population will surpass as much as 9 billion people at current growing rates (UN, 2016). Global water security is a challenge of sustainability; having enough water to quality standards whilst still ensuring environmental protection. In urban context this is particularly difficult through economic development and an increased per capita demand (UNEP, 2013a), resulting in continuous pressures to area's water reserves.

With recurring problems due to either climate change or population growth, water is nowadays either being polluted or scarce. This is posing dangers to human survival and is therefore eminent to be managed effectively. Strategic planning on water cross-refers multiple levels of the economy, on either a local, regional and national level. Therefore, effective planning exerts a large responsibility in being integral in the development and sustainability of the local economy, health and well-being (Van Leeuwen, 2016; Koop et al., 2017).

Amongst many others, multiple studies regarding urban, sustainable utilization of (fresh)water sources have been published, tackling several of the pragmatic problems arising through water resource distribution and allocation (Sahin et al., 2016; Marlow et al., 2013 ; Modastavi et al., 2018; Butler et al., 2017; Van Leeuwen et al., 2016). Nevertheless, many of these studies are rather focusing on localized, specialized problems concerning sustainable utilization of (fresh)water resources, focusing mainly on either urban water supplies (Modastavi et al., 2018), recycled water or water reuse (Marlow et al. 2013), integrated but localized assessments (Van Leeuwen et al., 2016) or the economics of water resources (Butler et al., 2017). Studies which are addressing the complexity of the system in a more holistic manner, remain scarce to this day. There has been a steady increase in the works published on water management, although only few of them address cross-sectional interconnectedness in the water departments.

To support sustainable utilisation of freshwater resources and towards sustainable economic and social development, this thesis uses System Dynamics (SD) methodology to simulate present conditions and future dynamics of freshwater use in the City of Cape Town (CCT), with a particular focus on desalination.

Specifically focusing on investigating water resources in the CCT is currently a necessity. Within the CCT, sub-Saharan weather variability has led to a 3-year failure to meet the set yield requirements by the government – resulting in a serious drought, whereas dam levels have been pushed to as little as 18% of their total capacity in May 2018 (GreenCape, 2018b). The government of the CCT is in fear of so called 'day zero' (Figure 1) – the day the taps in the city are portrayed as 'running dry'. In this scenario, the reticulation network will be severely restricted with residents constrained to a daily ration of 25 litres of drinking water/person/ day.

As water demands continue to grow and dams within the Cape region are almost reaching their limit capacity, CCT is one of the South African coastal cities that are considering augmentation programs as a potential future water supply source. Within the supply mix, one can manage water through infrastructural enhancements in groundwater extraction, water re-use, storm water harvesting or desalination.

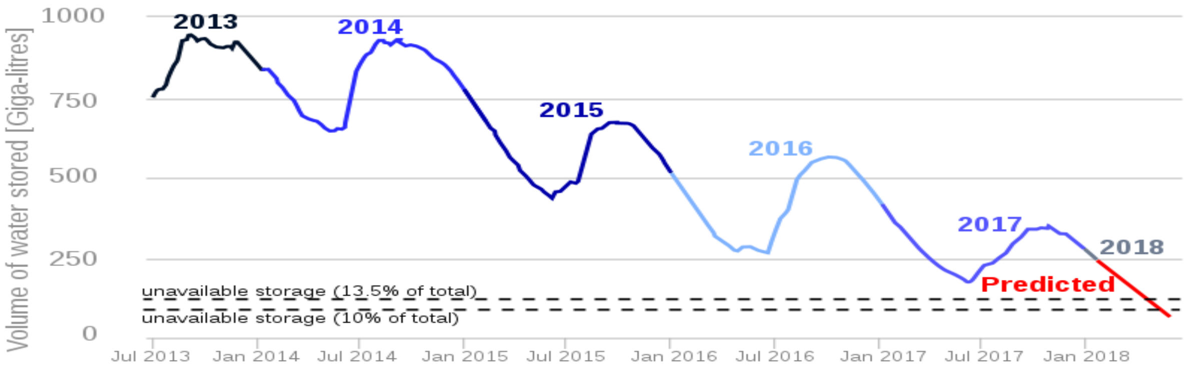


Figure 1. Water depletion in the CCT 2013-2018 (GreenCape, 2018a).

This research chooses to focus on desalination as this is different to more conventional surface and groundwater supply sources as the method is completely climate-resilient, thus obtaining an assurance of supply of essentially 100 percent (Blersch & Du Plessis, 2017). However, the increased reliability comes at a cost. In an attempt to ensure sustainable development, this research explores the multiple costs and benefits in their interdependent forms in an attempt to seek exploration to the following research questions:

In what way is the implementation of desalination in the City of Cape Town viable over a period of 50 years considering financial, socio-economic and environmental impacts?

Subsequently, the research adapts several sub-questions with the purpose of supporting the main question, which are:

- *How do additional costs of desalinated water add to the water price over time?*

- *How does desalination positively add to the economy of the City of Cape Town in the long run?*

- *What are the potential long-term effects of implementing permanent desalination on the marine environment?*

- *To what extent are Participatory Modelling approaches useful to support water management decisions in complex scarcity contexts?*

This thesis is structured in the following order. Firstly, after the introduction which shortly captures the relevance of this research, water scarcity-related issues are introduced in the form of an extensive literature review. After explanations of central concepts of the thesis, forms of both supply- and demand management are introduced. After, the argument is made as to why the method of System Dynamics is seen to be the best fit for this research. Chapter 3 introduces the case study, where the problematic situation of the CCT is sketched and its possibilities in both supply- and demand management to mitigate this problem. Chapter 4 (the Method section) introduces the procedures used to convey the model, whereas Chapter 5 consists of both the conceptual as the quantified model and its in-depth reporting of desalination. In Chapter 6, the discussion section, the implications, scenario-setting and effectiveness of the so-called 'model in conversation' approach are discussed. Lastly, the research questions are answered in Chapter 7, which is the conclusion section. Supplementary information, validation and other materials supporting the conception of the model are to be found in Annexes.

2. Literature review

2.1 Water scarcity as an emerging worldwide challenge

Around 70% of the Earth's surface contains water. From this amount, 97.2% is the salty, undrinkable form of water – whereas only 2.8% of the total water is located in a freshwater source. Additionally, a total of 61% of this freshwater is located in the hardly accessible Arctic Ice Sheet (USGS, 1993; Stephen, 2018; Rignot et al., 2011) which leaves the habited Earth with a total of 1.2% of accessible, potable water.

Water scarcity already affects every continent. Around 1.2 billion people, which is around one-fifth of the world's population, live in areas where physical scarcity of water occurs, and 500 million people are approaching this situation. Another 1.6 billion people, or almost one quarter of the world's population, face economic water shortage - where countries lack the necessary infrastructure to take water from rivers and aquifers (Qadir et al., 2007; EEA, 2017).

Over the last three decades, the perception on water has gradually changed to what it is perceived to be today; a renewable but scarce source. The common belief on water around 50 years ago was one of infinity, as in this time only half the amount of the world population existed. Both the meat and agricultural industry were around one third of the size to as it is now (Statista, 2018), resulting in the volume of one third of the water that we currently extract from rivers (as meat production utilizes a substantial amount of potable water for both growing feed crops for cattle as well as water consumption by cattle (Jacobsen, 2006), leading to an estimated 80% to 90% of potable water use in the US (USDA, 2016). In the present day, the competition for water resources extends to a far stretch.

2.2 Key Concepts

In the present research, some of the key concepts in the water jargon needed to be defined upfront to create a unified understanding, amongst others (found in Annex I). The main terms used in this thesis include "Water scarcity", "Water stress", "Water shortage" and "Water Gap".

Water scarcity:

The excess of water demand over the available water supply (World Economic Forum, 2015).

Water stress:

The system symptoms expressing water scarcity or shortage, translated into the conflict that arises between water users, the downward trend in standards of water quality and harvest failures. Multiple circumstances due to water scarcity are covered by the term (FAO, 2007).

Water shortage:

Low levels of the water supply as a result of insufficient resources or as a result of annual differences in climate. Water shortage is an absolute concept (FAO, 2012).

Water gap:

A period of time where water demand is exceeding supply and therefore drains the (dam) water supply of the urban area (DWA, 2013).

2.3 Dimensions of water scarcity

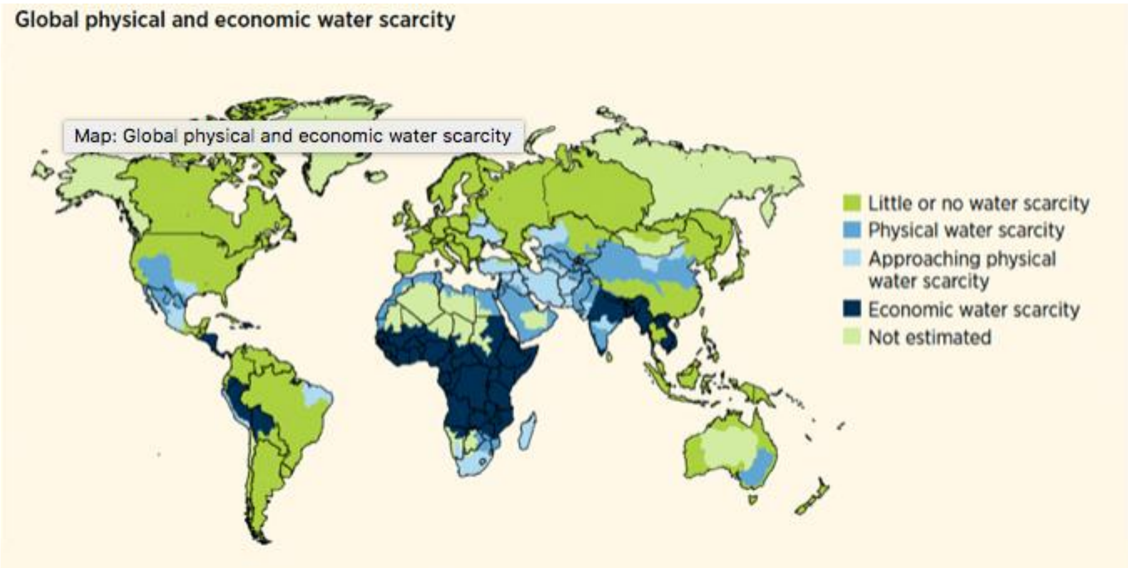
For many centuries, water systems have benefited people as well as their economies. The services these water systems provide are to be utilized to a wide extent. Nevertheless, in multiple regions around the world - mostly in developing countries - people are still not able to meet their daily basic water need, let alone sanitation. Causes for this phenomenon can be reflected back to a form of inadequate or degraded infrastructure, the overutilization of river water flows, overconsumption of industrial/agricultural industries, or just scarcity in resource (Hoekstra & Mekkonen, 2016). The basic principles of water availability are proposed by Seckler (1998) to be divided into two categories: <u>physical</u> scarcity and <u>economic</u> scarcity– whereas one is a lack of water due to natural conditions and the other one due to (mis)management and resource scarcity.

2.3.1 Physical scarcity

In some countries, there is a physical lack of water – these areas are mostly the areas where small development of life occurs (WWAP, 2017). Inhabited parts where there is a physical lack of potable water are often small in density. Most often, these regions are the poorer ones since cities commonly all have developed around a water source.

2.3.2 Economic scarcity

Arguably, most of our current global water problems arise from an economic point of view. Economic water scarcity flows out of the lack of investment in water needs, a lack of capacity to satisfy the demand for water. In the developing world, it is often time-consuming and expensive in finding a reliable source of safe water whereas needs cannot be satisfied due to infrastructural need. Simply put, water can be found, but it requires more resources to do so (TheWaterProject, 2016). It requires planning and structure from a government to tackle the issue of economic water scarcity, which is a perquisite developing countries mostly do not have (DOH, 2017). In the form of economic scarcity, water might be distributed inequitable. Map 1 provides the allocation of either physical or economic water scarcity.



MAP 1. GLOBAL PHYSICAL AND ECONOMIC WATER SCARCITY (WWAP, 2017)

2.4 Indicators of water scarcity

The widely-known indicator of national water scarcity is the amount of renewable water per capita. The indicator can be easily calculated through data analysis from each country for each year together with available population data of countries, measured by the Food and Agriculture Organization (FAO, 2012). Although useful, the measure is considered to be fairly oversimplified as it does not take local factors into account with regard to local access to water, climate conditions of the country, socio-economic factors, the potential for recycling purposes, water quality and most frequently utilized method of water sanitation (Molle & Mollinga, 2003).

To better capture the relationship between water supply and water demand, the Millennium Goals Water Indicator (UN, 2012) attempts measuring the water stress in a ratio comparison between the total withdrawals performed by agriculture, industries and cities over the total of renewable water resources of a country. Although a solid attempt, the indicator fails to provide reliability concerning the water withdrawals as e.g. leakages can occur.

The United Nations (UN, 2016) reconsidered and responded with a third water stress index, which presented the indicator to be “the percentage of water demand that cannot be satisfied” or within the jargon, ‘the water gap’ (UN, 2006). Although with difficulties in measurement as the indication can be regarded as fairly generic, this indicator for water stress (and thus, indirectly, water scarcity) can provide insight on surplus of demand towards the available supply.

2.5 Driving forces behind water scarcity

Global water use has been, and still is, rapidly increasing during the last century (at current rates, the use has been growing twice as fast as the population increase rate (FAO, 2009)). The drivers of this phenomenon are known to be due to demographic growth, development of the economy, urbanization and growing pollution, current water structures are now being pressured in their supply (FAO, 2009).

2.5.1 Drivers affecting water supply

The annual water volumes of water supply mostly fluctuate through climate and geographical conditions of the aimed land. Additionally, geological structures of the land determine its groundwater recharge as well as the storage facility for the given area. Rainfall can be considered the most fluctuating driver of importance for water availability (PWC, 2017; FAO, 2010). Rainfall translates in two main sources of potable water - river runoff and aquifer recharges - respectively supporting dam water resources and groundwater resources. Human interventions now are developed to such an extent that they have the ability to regulate the water supply to a far extent (FAO, 2007). Water control, by building dams and multipurpose reservoirs, can decrease variability of seasonal changes largely and provides us water on a regulated basis. A further option of underground storage is increasingly frequented as it is regarded as a convenient alternative to dams through their ability to disregard evaporation as these are constructed under the surface.

The (re)generation or augmentation of freshwater supply can be found in new developed methods as inter-basin transfers, groundwater extraction, desalination, the reuse of wastewater, storm water harvesting or importing water from other areas that are outside of the system, either by tankers or bags (Arafat et al., 2017).

The quality of water is ought to be regarded in relation to water supply as water quality determines the 'actual' usable amount of freshwater supply. Water quality tends to deteriorate through for example increasing re-use or contaminants in the water (e.g. fluoride) which are linked to ground water overdraft, resulting in a reduction of the availability of freshwater supply (Giordano, 2009).

To define the quality of water, one has to consider technical and socio-political dimensions (Lankford et al., 2013), which has the requirement of understanding the technical processes of the provision of water supply as well as the social values regarding the timeframe (what humanity reasons as 'acceptable' in that particular time-and-place frame). These standards are usually set by national authority or international standardization; on less dense/ prosperous locations, a quality issue is locally regulated. All in all, a set prescription of water standards inevitably would lead to a reduction in the total amount of water supply available (which, in the Cape Region (Figure 1), results in the 10% 'unavailable storage' of the dams).

2.5.2 Drivers affecting water demand

Drivers which are most directly affecting water demand are the growth rate of population and the changes in consumption of population – especially the water considered for their daily dietary needs. Indirect consumption of water takes place through e.g. water power plant generation, recreational use of freshwater (pools) and environmental errands (UNEP, 2013b). An indirect use of water can also be considered through population's changes in land use as well as the changes in behavior of water use. The stress on the water index arises as global income grows (UNEP, 2013a) – people are less satisfied with a large amount of water.

The global average food supply is estimated to rise by 30% in the projection of 2050 (Alexandratos & Bruinsma, 2012), which would translate into an added production of (amongst other water consuming production processes) 200 million tons of meat on a yearly basis (Alexandratos & Bruinsma, 2016).

A second, major driver is the demand for agricultural water. This agricultural driver accounts for around 70% of the total demand of freshwater. Within an urban context, this dominance is shifted to domestic use as water here serves the purpose of sustaining a large conglomeration of people rather than vast amounts of land. Typically, water demand in urban areas consists of around 65-75% of domestic use (PWC, 2017).

As climate change occurs, the distribution of freshwater for agricultural purposes is endangered; for production of crops, a significant amount of water is needed. More severe droughts will occur through climate change which eventually will affect the local production of crops. This will likely lead to more pressure on surrounding agricultural areas that are more rain-secure, considering an exponential shift towards import of production to reduce food insecurity in less rain infested areas (De Clerq, 2018).

2.6 Previous responses to water scarcity management

In extreme weather conditions, local responses have been performed in various forms. This selection of illustrative cases (which are randomly selected for each form of augmentation) represent multiple forms of mitigation or hedging action to either avoiding a problematic water situation, or (in)effectively dealing with the situation in a real-life context, to be seen in Table 1 and further explained below.

TABLE 1: SELECTION OF RESPONSES TO WATER CRISES

CITY / COUNTRY	RESPONSE
CALIFORNIA, USA	Groundwater extraction
LIMA, PERU	Water reuse
CHENNAI, INDIA	Water reuse
KEMPALA, UGANDA	Decentralization of water
DURBAN, SOUTH AFRICA	Circularity of water
THE UNITED ARAB EMIRATES	Desalination
SINGAPORE, SINGAPORE	Synergy approach

<u>Groundwater extraction and its effects: California</u>

Due to high temperatures, high demand and high evaporation within California (USA), the state encountered a large drought with its peak in 2007-2009. In an attempt to reduce the pressure of water in a most efficient and urgent way (since the government had maintained a reactive strategy regarding water management, resulting in dam levels to drop to a critical extent) the government responded predominantly with an extra pressure on extraction of groundwater sources (USGS, 2014). Currently, large desalination plants have been put in place to maintain a steady income of water whereas this at the time would take on average 4-6 years to construct. Nevertheless, the aquifer extraction system is still operational. The Central Valley aquifer (52,000 km^2), now supplies almost 7 percent of the United States' supply of food. At this point, the aquifer supplies nearly 20% of the state's demand of water (Kenny et al., 2009), although scientists are showing evidence of several anomalies arising in the groundwater basin after being extracted permanently (NASA, 2012; USGS, 2014).

Wastewater reuse in metropolitan areas: Lima & Chennai

As a result of climate variability and extended periods of drought through the La Nina phenomenon, the Andes is losing its glaciers which accounts for over 60% of Lima's water supply. Lima, capital of Peru, is gaining rapid urbanization counting up to 15 million people; as water is already scarce since it receives hardly any rainfall, adequate solutions are ought to be found. Within their water development plan, the government of the city of Lima issued a rigorous goal of implementing as much wastewater reuse as is needed to complete water re-usage for 100%, or 24.8l/s, by 2035 (World Bank, 2015). Their approach is one of learning by doing; it still has to play out whether their procedure works. Nonetheless, the city of Chennai approached their similar scarcity issue with a more structured, bottoms-up approach: through strong coordination and governance, the metropolitan area established a water recycling program which has the potential of reaching 100% sewage collection claimed by the Chennai Metropolitan Water Supply & Sewerage Board (CMWSSB, 2018). The city established to reform their water ways (whereas for example all toilet sewerages were replaced with recyclable water) in such a way, that this accelerated form of wastewater reuse is maintaining service standards together with the goal of zero water discharge.

Water management in sub-Saharan context: Kampala & Durban

Kampala, a growing city in sub-Saharan Uganda, recently received worldwide recognition on their integration of water management. The city responded to the high variability of supply through climate with teaming up internally (NWSC, 2006); the city takes an inclusive city-wide approach to accelerate sustainable water management. Solutions are found in both water demand management and decentralized sanitation systems. Since 60% of its population is living in informal settlements, the burden on water pricing cannot exceed certain limits, therefore the city has chosen to focus on decentralized sanitation systems – on the path of a circular water economy, the city is increasing their water treatment plants and implementing water reuse plants on tariffs of the government (NWSC, 2006).

Further down in South Africa, the city of Durban has proven innovation on water to give exceptional results. Whereas Durban is a subsequent case as Kampala both in their economic and demographic situation, an economically viable option for the city has been found in the form of putting wastewater to an economic good. To completely decentralize their management on water, they put water competition up to the market. The government only has policy control whereas the local city is financially and administratively fully autonomous. This has led to a 20-year contract of the Durban Water Recycling organization Ltd. whose overall objective is to treat approximately 10% of all the city's water to potable standards. (Durban.gov, 2017)

Water without source: The United Arabic Emirates

In most of the countries in the Middle East, research has shown that population growth rate is slowing down and will even slow down increasingly in the upcoming 10 years, according to the ESCWA (ESCWA, 2016). However, domestic water use is steadily increasing due to urban water demand and expectation patterns; in the UAE, domestic water use is shown to be the highest in its region. Although the UAE is located in a desert area where surrounding water is nowhere to be found, the country is known to have the highest per capita water use (mostly through requirements for oil production) in their area, accounting up to 550 liter per person per day on average (Ecomena, 2015). To compensate the water use, the Middle East invested heavily in the production of desalination plants, whereas the UAE now has a share of 14% of the global desalinated water (Statista, 2015).

Transitioning synergy to weather independence: Singapore

Singapore is a relatively small, wealthy city state in South East Asia. With limited demographics for water catchment structures, Singapore was tied to purchasing water from neighboring Malaysia under a total of two water agreements (PUB, 2011). This dependency on their neighboring country had been perceived as a liability to the sovereign state (Biswas et al., 2013). Through the increase of intensity of extreme storms within the urban area, allowing for flooding of residential areas, a program for an underground water storage system has been proposed in early 2012, whereas this structure is being used for storage in emergency situations. However, although weather conditions are seemingly ‘over productive’, Singapore is a fast-growing population with water scarcity as local water catchments are both fairly limited and the tropical climate in the country speeds up evaporation in these structures. To avoid getting into a water crisis where they would be dependent on Malaysia, Singapore has heavily invested in renewable water augmentation over the last decade (PUB, 2011). This program, branded as NEWater, is a combination of desalination, efficient water catchment management, water re-use structures and additional projects. This project has resulted in an integrated approach towards management of freshwater resources on an urban scale.

These selected cases only include a single form of augmentation, chosen by the subsequent governments to focus on. Reason for the implemented augmentation might find its foundation in demographics, availability of money, effectiveness of option or level of reassurance. All of the selected cases are already implemented to completion or are rallying towards completion. However, the reason why these methods are chosen remains reasonably unclear on paper. A systemic assessment might be able to support the decision-making on ‘making the right choice of augmentation in common consensus’ for a city; this thesis tends to explore exactly these options for the choice of augmentation. The following subchapter will provide an extensive overview of the available components in the water supply and demand paradigm.

2.7 Managing water

In the fear of climate change together with a growing population, effective water management ought to take a highly sensitive stance in order to cope with future issues – allowing water levels to drop down to zero is not an option as freshwater is needed for survival. Management of water can be dealt with either on the supply or the demand side. Table 2 represents the main management options for both sides, followed by an extensive review on all options on both the supply and demand side.

TABLE 2: OPTIONS ON BOTH WATER SUPPLY - AND DEMAND MANAGEMENT

SUPPLY OPTIONS	DEMAND OPTIONS
DAM EXTENSION	Educational programs
GROUNDWATER EXTRACTION	Water tariffs
WATER REUSE	Water taxes
STORMWATER HARVESTING	Forced restriction
DESALINATION	Intrinsic motivation

2.7.1 Managing supply

The management of supply is vital for ensuring the water provision to people. When there is no water supply available, the economy of the location is at stake. Water supply therefore needs to be planned for the long run accounting for factors as population growth and climate change. To ensure that this thesis covers all main options of supply, an extensive overview on water supply options and possible extensions is given below.

Dam water extension

In current context, humans are primarily reliant on the water supply of dams. Dams are usually placed in catchment areas with the highest density of rainfall (MIT Terrascope, 2017). Nevertheless, placing dams destroys the ecological structure of the area and is therefore ought not to be placed in any conserved area (WWF, 2017). A dam is a catchment structure, stopping a river from flowing through; effecting the river runoff in further areas rendering that river water to essentially zero. In demographic situations where possibility to build new dam structures is limited (either to river conservation, environmental standards or limited rainfall throughout the area), current dams are mostly extended in size or being more optimally managed in their capacity (MIT Terrascope, 2017).

Groundwater aquifer extraction

A possibility to augment current water supply is building structures to extract groundwater resources from aquifers. This practice has been commonly performed throughout the last 40-50 years on various water-tense places all around the world. Within an aquifer, water fills up through seeping water through leaks of the aquifer, allowing the water to store for multiple years (Nevill et al., 2010). Although a fairly cheap practice, the danger to extract from groundwater reserves lies in the restoring capacity of the aquifer and the common use by the biologic sphere of the groundwater. It is groundwater depletion that is a worrisome key issue in groundwater extraction; excessive pumping can overdraw the groundwater storage.

Water stored in the ground can be seen as money that is being kept in a bank account. Withdrawing (depleting) money at a faster rate than depositing (replenishing) will eventually cause problems in account supply. Although aquifers replenish, this usually happens on a slower rate than withdrawal might the aquifer be (over)drawn as a form of augmentation. It is proven by multiple sources (USGS, 2014; Nevill et al., 2010; Zektser et al., 2005) that groundwater depletion can lead to various negative consequences - the drying up of wells, reduction of water in streams and lakes, the deterioration of water quality, increased pumping costs and land subsidence. A visible showcase can be found in Mexico City, where large areas of housing units built directly on an aquifer are lowered in the last 10 years by around 23 centimeters as a result of groundwater pumping (Tortajada, 2008; Shelley et al., 2017).

Crucial for long-term sustainability is the reduction of water in streams and lakes. A large part of the water flowing in the rivers comes from seepages of groundwater in a riverbed (USGS, 2014). Groundwater inflow contributes to these streams depending on the region's geology, geography and climate. Groundwater pumping however, can alter how the water moves between an aquifer and a river - which then would be a reduced inflow into water dams. It either intercepts groundwater flow that discharges into the surface-water or it lowers the groundwater levels below the depth that the wet-land or streamside vegetation needs to stay alive. An overall effect is therefore also the loss of vegetation in these areas, or the loss of wildlife habitat.

<u>Water re-use</u>

A fairly recently developed form of augmentation is the ability to re-use water which is being used for sanitation purposes. One can think of flushing a toilet; whereas in many cities this water is being installed as drinking water, this water does not have to maintain the same water quality standards as drinking or showering water. Therefore, with the use of new techniques it is possible to reallocate this water to a 'cleansing-and-redistribution' structure, allowing the toilet water to be used twice instead of only once.

Current urban areas have large room for growth in water reuse structures. Nevertheless, it is a fairly difficult and expensive procedure to implement; a reconnection on the water reuse structure rendering to a reuse scheme of 100% would mean that there should be changes in every individual domestic and public sanitation facility. This is a costly procedure which eventually will get back to the people in the form of water tax. Together with a reassurance of around 99% (whereas if the surface water runs out there is no water to re-use (Blersch & Du Plessis, 2014)), most governments see water reuse as a fairly underdeveloped and difficult method to implement.

<u>Desalination</u>

Desalination (also called 'desalting') is the process of removing dissolved salts from water, thus producing fresh water from seawater or brackish water (IDA, 2015). The most prevalent use of water desalination is the production of potable water from saline water for domestic or municipal purposes. Reverting saltwater to potable water on a large scale, for provision of majorities of households, inevitably needs a large-scale volume of water conversion which is mostly extracted by collective water plants (IDA, 2015).

Desalination systems have long proven effective in Kuwait, Bahrain, Qatar, the United Arab Emirates, Oman, and Saudi Arabia. According to the International Desalination Association (IDA, 2015), in June 2015, 18,426 desalination plants operated worldwide, producing 86.8 million cubic meters per day, providing water for 300 million people. This number increased from 78.4 million cubic meters in 2013, which is a 10.71% increase in 2 years.

Through technological developments a handful of methods have been created to extract saltwater into potable water, of which vacuum distillation still is the traditional process conducted most frequently. Nevertheless, there appears to be a growing trend in the use of the process of Reverse Osmosis (RO) as this method uses less thermal energy than traditional processes.

It is up to the government to decide when and how to implement additional structures to manage their water supply. Water supply management is a trade-off of finance and assurance of supply. Basically, water augmentation comes down to payment for assurance. In current state-of-the-art of technology, the more assured a country strives to be, the more expensive the option is. The relatively cheap technique of groundwater extraction comes with uncertainties and dangers for environment. Water re-use however, has a reduced uncertainty but is a relatively expensive method to implement. The fallacy of water re-use is water availability: in case there is no water available, there is no water to be re-used. Finally, desalination is a full assurance of supply in the assumption that the plant does not experience any technical failures. Nevertheless, desalination is relatively the most expensive option of augmentation.

2.7.2 Managing demand

The extent to which water demand is 'negotiable' is central to coping strategies for water scarcity. Water to satisfy basic needs such as drinking, sanitation and hygiene is effectively non-negotiable, but it represents only a small percentage of water demand. In a similar vein, the 'human right to food' concept is increasingly recognized. The production of food requires huge quantities of water, determined by the fundamental biophysical processes associated with food production. There is therefore a non-negotiable volume of water needed to ensure safe and sufficient food for everyone (Steduto et al., 2007). Despite this, sizeable changes are possible in the way water is used to produce food. For instance, the choice of crop type cultivated under irrigated or rainfed circumstances, the number and type of animals to be raised, farming practices and irrigation technologies in combination with their associated productivity levels, changes in the spatial distribution of production (implying trade), and changes in social habits (consumption and distribution of food, diets) can all reduce the overall demand for agricultural water and offer room for maneuver.

A government can implement water demand management in many ways - either trying to create an intrinsic understanding through governmental education programs on water (Water4CapeTown, 2018) or by imposing water restriction laws, paired with fines when this amount is exceeded. In addition, it is a sense of prioritization of the government; different laws can be imposed for the use of water on farmland, which makes up for the (re)distribution of water (DeClerq, 2018).

To keep restrictions justified for people, water taxes should principally only be imposed when water supply does not meet the level of demand; an individual is hard to convince when there is no empirical evidence on reduced water availability. This is characterized as a rather ‘reactive state of response’ in water demand management (Koch & Vogele, 2009). A form of proactive behavior on water demand management would be to implement governmental awareness programs where people would become aware of water by any means possible. To educate people on water might reduce their domestic patterns over time as an intrinsic value in themselves has changed. This initiative is cross-sectional; for example, in the form of environmental organizations or NGO’s addressing the need of water reduction.

2.8 Systemic analysis of water

Water scarcity is fundamentally dynamic, with much variance in time as it is liable to approaches of management and planning as well as the societal capacity in anticipating to variability of supply and demand. Problems in short-sighted policies such as expansion of agricultural sectors by basically giving out cheap water for the farming industry, gets intensified by the increasing demand of potable water usage whereas the availability of this potable water decreases. The resulting water stress is ought to be identified correctly – mostly to improve water access where yet only small arrangements are made. It is an infrastructural issue: when the dynamics are identified correctly, many causes of scarcity might be predicted, and the likeliness of avoidance or mitigation of these issues can increase.

Dynamics are to be found in the interplay of water demand and water supply, especially in connecting water to finance. In water scarce countries, socio-economic politics are requiring attention as water improvements or augmentation (leading to an enhanced assurance of supply) could possibly be detrimental to the economy of the country as the cost of production of this augmentation would get too high.

Water management is closely interrelated with environment management. To introduce more structures on water augmentation or expanding dam capacities in multiple countries one is forced by law to regard an environmental assessment of the proposed infrastructure design (DWAF, 2007). This is because within basically every available method of augmentation, the environment is at stake. Dam expansion resolves in a deterioration of biodiversity in the on-flowing rivers, groundwater extraction is feeding the environment on its reserves, and desalination would resolve in the expulsion of brine which would then affect the marine biology negatively. Therefore, water management should be multifaceted and look beyond the borders of solely humanity as a potential life-form at stake.

On finance, one encounters an uncertainty towards payment. Since water is seen as a governmental provision, water is mostly centralized in its management. However, government might not comply to the people's wishes whereas private funding and organizational money comes in. To see water as a private, decentralized good is a new approach being introduced especially in countries where the government is regarded as financially unstable (Bakker, 2003). Water becomes a product, subject to the market. It is a play between supply and demand, whereas all water is subject to national and even international quality standards.

In summary, within the context of water management, one encounters multiple complexities, uncertainties and interdependencies. To account for all these factors, multiple complex modelling tools should be analyzed to provide a right fit of method with the issue at hand.

2.9 System Analysis

A first step of identifying and addressing a water resource system is to make an accurate assessment of the water supply resources that are available and their use, forming the basis for future predictions. Milestone work on the expertise of water mapping includes papers of Shiklomanov (2000), Gleick (1993) and L'vovich (1974). Although these studies address a static system based off quantitative data of river runoff, these systems do only grasp at the concept of interrelationships between variables and presume these variables to be implicit in their system. In their analyses spatial and temporal dynamics are lost in integration, therefore the methods used in the studies contain a rather static representation of the real-life dynamics. Although scarce in early stages, several studies have been conducted that do capture water dynamics (and are dynamic by nature) in the form of globally applicable tools. Amongst others, two that have been found relevant enough to implement is the TARGETS tool, initiated by the Rijksinstituut voor Volksgezondheid en Milieu (RIVM (National institute for Public Health and Environment), 2003) in the Netherlands and the World Water Model, developed by a group of researchers under the lead of Simonovic (2002). In these models, dynamic feedbacks of water resource systems are captured in the form of a sub-system of a larger model.

The TARGETS tool, a Tool to Assess Regional and Global Environmental health Targets and Sustainability, is a concept of multiple five integrated meta-models - land use, population growth, energy, biochemicals, and the water sub-model. The model attempts to capture interrelationships between the sectors in the Netherlands, targeting to create a model framework which could be integrated with other countries with other parameters. Interestingly, several human related functions are integrated in this model; amongst others, the model factors in human behavior on demand, water usage behavior on agriculture, construction delays and water consumption reduction (RIVM, 2003).

The World Water tool, a system created as a decision support tool on multiple issues in Canada, uses a System Dynamics approach to capture the internal feedbacks of seven sectors: population, non-renewable resources, persistent pollution, economy, agriculture, water quality and water quantity. Its water sub-model includes precipitation, non-renewable groundwater resources and ocean resources, with optional water re-use. Water usage contains population growth and urban demand (Simonovic, 2002).

2.9.1 Choice of method

Whereas many conventional methods represent relationships in water systems statically and linearly, the context of this thesis is to connect sectors and reveal the complexities inherent to these interdependencies. Therefore, the research is in need of adopting a modelling tool appropriate for the purpose and complexity of the matter.

To model the water supply and demand system and its interdependencies, this thesis adopts the reasoning through the decision tree of Kelly et al. (2013). The model is an exploratory model, whereas little research has yet been done on the aggregated effects, rather on the single effects. This research demands to analyze the breadth of the system as the water system has not yet been generalized in current research. The presence of feedback loops is evident (e.g. the cross-sectionality of environment pressures and water costs), and a system that captures various elements on different levels of detail has not yet been produced for the CCT. A System Dynamics model therefore holds the best argument in choosing the method for the decision support tool (Decision tree to be found in Annex X, Figure 1).

To set a more grounded argument, the method is compared to other methods. Further in Kelly et al. (2013), features of multiple methods are being compared in regard to their respective requirements. In relation to the requirements of systematically mapping the water system (Annex X, Figure 2). Yet still, it is concluded that System Dynamics still is the best fit for the purpose of the model which was argued through the decision tree. The model seems to have strong similarity in critical points with a Bayesian networks model. The Bayesian networks method is a probabilistic graphical model that represents a set of random variables and their conditional dependencies via a directed synthetic graph (Ben-Gal, 2008). In relation to the purpose of this research, this method shows suitability in its capabilities of being aggregated, broad and for the purpose of systems understanding. However, since this is an exploratory model, it is fairly unjustified to provide explicit information about the uncertainty caused by the assumptions. It is too narrow to distinctly reason why an uncertainty is created in the case of a water system; there are too many interdependent uncertainties to rule out 'only one option'. Assumptions can be found and captured in feedbacks instead of through the model assumptions. Therefore, the most critical point System Dynamics is distinctive to be the right fit for the selection over the Bayesian Networks method is about model purpose; the Bayesian network method is considered to be too exacting and predicative for the purpose of this research.

2.9.2 Overview of System Dynamics application to water issues

System Dynamics (SD) is an approach with the aim to understand the behavior of complex systems over time (Forrester, 1970). It captures internal feedback loops and time delays that affect the entire system. Developed by Professor Jay Forrester in the

1960s and popularized by the Club of Rome's Limits to Growth in the 1970s, System Dynamics has been successfully applied to study business development, demographics, natural resources management, environmental systems, and most relevantly, water. The capability to simulate consequences of the implementation of various policies on the system in a dynamic manner make the tool ideal for decision support for the selection and testing of strategic policies. The current modelling studies of water resources mainly focus on the irrigation system of the agricultural industries. An overview of all articles used for defining the State-of-Art in SD is presented in Table 3, in order of appearance.

TABLE 3: STATE-OF-ART OF SYSTEM DYNAMICS APPLICATIONS TO WATER MANAGEMENT SYSTEMS.

Publication	**Authors**
Multi-model assessment of water scarcity under climate change.	*Centre for Systems Research (2000)*
WorldWater: A Tool for Global Modeling of Water Resources.	*Simonovic (2002)*
System dynamics modeling for community-based water planning: Application to the Middle Rio Grande.	*Tidwell et al. (2004)*
Integrated system dynamics toolbox for water resources planning.	*Tidwell et al. (2006)*
Using system dynamics for sustainable water resources management in Singapore.	*Xi & Poh (2013)*
System dynamics simulation model for assessing socio-economic impacts of different levels of environmental flow allocation in the Weihe River Basin, China.	*Wei et al. (2012)*
Mental Models in Urban Stormwater Management.	*Winz & Brierley (2009)*
Collaborative modeling for decision support in water resources: Principles and best practices.	*Langsdale et al. (2013)*
Scoping river basin management issues with participatory modelling: The Baixo Guadiana experience.	*Videira et al. (2009)*
Featured collection introduction: collaborative modeling for decision support as a tool to implement IWRM.	*Van den Belt et al. (2013)*
Mediated modeling in water resource dialogues connecting multiple scales.	*Van den Belt & Blake (2015)*
A system dynamics model to facilitate public understanding of water management options in Las Vegas, Nevada.	*Stave (2003)*
Chapter 6: Using System Dynamics Modelling in South African Water Management and Planning.	*Clifford-Holmes et al. (2017)*
Water security through scarcity pricing and reverse osmosis: a system dynamics approach.	*Sahin et al. (2015)*
Examining the potential for energy-positive bulk-water infrastructure to provide long-term urban water security: A systems approach.	*Sahin et al. (2016)*
CFD modelling of marine discharge mixing and dispersion.	*Robinson et al. (2016)*

A first attempt to model water scarcity as a whole in the field of systems methodology has been done by the CESR (2000), in an attempt to simulate global water scarcity in a scenario-setting framework up to 2025, which has made room for research in water dynamics. A systemic analysis on the water supply system of regional to global scale has been done by Simonovic (2002) by integrating a systematic assessment on the individual factors the water supply and demand system usually contains.

A System Dynamics approach for modeling community-based water planning was applied in the Middle Rio Grande, New Mexico by Tidwell et al. (2004). They deployed system dynamics to balance ta highly variable water supply along with the demands that are posed by urban demand – by combining stakeholders form the city who input is captured in their model. In Tidwell et al. (2006), the research is generalized and conformed into a “toolbox” - a specialized decision framework supporting tool that interactively engages the public in the decision-making process and integrates over the myriad values that are of influence for water policy. This toolbox is put up by the use of System Dynamics with a - claimed - adequate integration of Geographical Information Systems (GIS).

In Singapore, the NEWater approach has been analyzed systematically via the method of system dynamics in a collaborative effort (Xi & Poh, 2013); the SingaporeWater model. This model investigates all available augmentation methods for Singapore, controlling for long-term sustainability. In this joint effort as part of multiple bachelors theses, results showed the supposedly optimal amount and time of implementation of augmentation matters. The research discovered that investing in underground water storage or conventional surface water extensions would not be sufficient to achieve self-sufficiency in water, which is a goal of Singapore’s Public Utilities Board (2011).

To assess socio-economic impacts of different levels of environmental flow allocation in the Yellow River in China, the study of Wei et al. (2012) adopts a System Dynamics approach. The study tends to reflect interactions between water resources, environmental flows and socio-economy by creating four growth patterns in socio-economic settings and four environmental flow schemes are designed to make a simulation of these possible impacts. In the results section, Wei et al. argue that the developed SD model performs adequately in the reflection of the dynamic nature and behavior of the system.

Winz & Brierley (2009) investigate perspectives and mental models regarding storm water management in New Zealand, using cognitive mapping (a form of soft system dynamics, merely causally mapping the model). The method was used to elicit and capture the perspectives of a total of 31 stakeholders on solutions, apparent obstructions and identified barriers to the implementation of storm water management. Their analysis confirms the conflict in perspectives, whereas they propose a quantified integration of solutions.

In combination with stakeholder engagement and water resources management, Winz et al. (2009) try to tackle the conflict in (amongst others) urban water management and try to integrate System Dynamics as a common denominator in the form of a participatory modelling process. Continuing, Langsdale et al. (2013) produced a guideline for principles and best practices in collaborative modelling for decision support in water resources. A set of eight principles is presented, followed by a selection of associated best practices. Their guidelines are presented in the line of two Canadian case studies; Operating Rules for the Lake Ontario- St. Lawrence River and Climate Change and Water Resources on the Okanagan Valley, British Columbia.

In a process of finding a shared view on the pressures, problems and possible impacts of the Baixo Guadiana River Basin in Portugal, Videira et al. (2009) put up a participatory modelling process with its affected stakeholders. Subsequently, a more in-depth analysis of the strong and weak suits of this participatory method in relation to river basin planning was created. It refers to group stability as one of the critical factors for participatory modelling – and creates a floor for adapting the method in different contexts with the involvement of stakeholders.

In the Manawatu catchment, the constructed model by Van den Belt et al. (2013) proved to be useful outside of the model itself. The model was used as a form of communication and education to a wider public than just the initial stakeholders; local farmers and fishermen were helped by means of the water catchment system dynamics model. Subsequently, Van den Belt & Blake (2015) observed a paradigm shift toward collaborative multi-level water management and integrated a decision support tool by means of Mediated Modelling (MM (van den Belt, 2004)), which is a form of Participatory System Dynamics Modelling (PSDM). In this research, the importance of participatory processes is underlined; in all the case studies that they observed it was shown that a participatory process was deemed to be most useful.

A more widely cited group model building effort in water management through System Dynamics has been performed by Stave (2003). Research aimed to increase the public understanding of the value if conserving water in Las Vegas. Through an interactive forum, the model had been put up whereas multiple feedback loops showed a rather counterintuitive insight for the likes of interested stakeholders. Reducing residential outdoor water use turned out to have a much larger effect on water demand than the reduction of indoor water use by the same amount (Stave, 2003).

In a South African context, Clifford-Holmes et al. (2017) observed a similar finding on the basis of three case studies: The Pongola floodplain, Sundays River Valley Municipality and Enhancing resilience in the Limpopo-Olifants catchment. All three of the case studies were undertaken within multi-, inter- or transdisciplinary environments- where in all three of the cases an either partial or full Group Model Building (GMB, Vennix 1999) process of System dynamics modelling had taken place. The modelling, as described by the researchers, provided a "means of understanding and responding to real-world problems, synthesizing knowledge, and providing potential decision support" (Clifford-Holmes et al., 2017).

In water desalination and RO studies through system dynamics, there are two current cases with similar problems; the drought in Australia (Sahin et al., 2016; 2017), and a systems approach on indexing desalinated water supply in Singapore (Xi, 2017). In Sahin et al. (2015; 2016a; 2016b), the potential for bulk-water support in Queensland, Australia has been investigated with a systemic approach. Its System Dynamics model analyzed the options for groundwater extraction and desalination in the realm of water supply and demand, showing much similarity with current research on water pricing in relation to scarcity and governmental burden for installments of more expensive water supply augmentation structures. For brine dispersion, Robinson et al. (2016) attempted a multi-stakeholder analysis with predominantly marine biologists, trying to capture the effects of brine from desalination in a Causal loop Diagram.

All in all, these studies all show the possible strengths and weaknesses of System Dynamics in water management. Relating System Dynamics to water management in the City of Cape Town is yet very scarce; this research seeks to provide a first attempt to capture these specific dynamic processes in water management of the CCT.

3. Case Study

3.1 The Sub-Saharan Context

On top of the challenges already imposed, is the variability of the climate in sub-Saharan countries restricting freshwater to a relatively low assurance of supply (Conway et al., 2013), adding another layer of complexity to the supply and demand management amongst these countries. The financial resources of these countries are usually limited, whereas a budget for water planning needs to be handled with caution to keep water pricing as low as possible. The water crisis in CCT is a product of these limited factors; a city that is being ‘pushed to its limits’.

3.1.1. The South African Context

South Africa is considered water scarce. The annual average rainfall is around 450 millimeters whereas the global average produces around 850 millimeters (World Bank, 2017). The country faces multiple challenges with this water scarcity, with amongst others the security of supply, environmental degradation and resources that are being polluted (DWA, 2013). A statement by the Department of Water Affairs (DWA[1]) identifies social development and South Africa’s growing economy as a threat to the country’s water security.

The total water demand in South Africa is expected to increase by 1.2% each year in the period of 2012-2022 (DWA, 2013). In-depth research by de Ridder & Moira (2011) suggests that - with price elasticity based projections predicting an increase of 62%, while historic figures predict a 30% rise for 2030 - a high level of uncertainty and variance coincides for water demand in South Africa. Under-investments in water infrastructure have led to a lack of maintenance in South Africa, resulting in an average of 37% of water that is being wasted through leakages in the water system, classified as ‘non-revenue water’ (DWA, 2013). For a National vision until 2030, the ‘National Water Resources Strategy (NWRS) has been issued. The overall goal is stated as “Water is efficiently and effectively managed for equitable and sustainable growth and development” (DWA, 2013) whereas the government pursues a total of three main goals:

[1] The organisation maintained the name Department of Water Affairs (DWA) until May 2014, after which it was renamed as Department of Water and Sanitation (DWS).

(1) the support of development and the elimination of poverty and inequality, (2) making a contribution to the economy and job creation and (3) that water is protected, used, developed, conserved, managed and controlled sustainably and equitably (DWA, 2013).

3.2 Current state of affairs in Cape Town

In Cape Town, South Africa, climate variability has led to a 3-year failure to meet the set yield requirements by the government – resulting in a serious drought, where dam levels had dropped to 18% of their total capacity by May 2018 (GreenCape, 2018b), of which its end date is rather uncertain due to climate variability and the ongoing effects of climate change.

Current research on the region all points to the decrease of the length of the rainy season, paired with extremities in rainfall events due to climate change– putting regional food security under appeal (Cornell et al., 2013). Although the year 2015 was an extreme measure, whereas it has been calculated to be the driest year in the CCT in 112 years, the Department of Water and Sanitation (DWS, previously DWA) identified the CCT to be the first major urban area in the sub-Saharan region where urban water demand is expected to exceed the potential water yield with a fairly high degree of certainty (Mukheiber & Ziervogel, 2007), if the various scenarios on population growth and regional climate change will be realized. Over the next three decades, it is projected by various sources that the CCT will endure an unsustainable impact with climate change, population growth and only a small possibility to increase the water yield from catchment areas (New, 2002; Du Plessis, 2018). In rigorous expectations, within the range of 7 years (2025), the CCT would be characterized as “chronically water scarce” (DWS, 2016).

The major portion of the CCT’s water resources are being managed and maintained by the Western Cape Water Supply System, the WC/WSS. The DWS (2016) states the yield of the water supply system to be 570 million m^3 per annum, as the total consumption of water in 2015 was 547 million m^3 per annum. If no intervention is made and the effect of climate change is not considered, the demand of the system yield is expected to exceed the water supply yield in as little as 7 years (DWS, 2016). To maintain water security in the city on a longer time period, the government is currently implementing a water resilience plan called ‘Cape Town Water Resilience Plan’ (CTWRP) which is a reconciliation plan on both the supply side and the demand side. Tackling the current crisis through pro-active behavior however has proven to be difficult on account of “bureaucratic inertia and tensions between the national and provincial governments, led by opposite political parties” (Wolski, 2018).

3.3 Demand management Cape Town

A first intuition and loud argument by the inhabitants of the CCT would be to fix the city’s water leakages. Nevertheless, this process is relatively expensive as it requires a new pipeline and non-revenue water in the CCT is a smaller issue than in the rest of the country since their water structures only are accounting for the leaking of 25% of the supply (McKenzie et al., 2013). The government still is trying to implement a water conservation strategy as a part of the CTWRP, called the Western Cape Water Demand Management plan (WC/WDM (GreenCape, 2016)). This plan aims to reduce the non-revenue water of the CCT to a minimum by installing either new water meters, more water efficient fittings and smart detectors on leakage and possible repair. Additionally, the plan issues user education in order to reduce wastage by water consumers (GreenCape, 2016).

Nevertheless, the CCT needed immediate intervention as a response to the drought, in order to avoid reaching critical dam levels. The government allowed proposals of scientists to have a voice in the decision-making – whereas for example the idea of an iceberg from the arctic was proposed and presented on UCT to gain the likes of academia (Sloane et al., 2018), but was rejected.

Drastic water demand management programs implemented by government in the first 6 months of 2018 prevented the dams reaching the critical point called ‘Day Zero’ – the day the taps were portrayed as ‘running dry’. In this scenario, the reticulation network will be severely restricted with residents constrained to a daily ration of 25 liters of drinking water/person/ day. Should people not comply with this measure, a heavy water fine will be imposed. The costs of these fines range between R4.560 and R4.730, and have already been imposed up to 500 times since 2016 (capetown.gov, 2018). Currently, the city is under level 6B water protocol which means that citizens are only allowed 50 liters of water per day. This stage can be regarded as a socio-economic disaster, whereas several reported riots on water plants have already been concluded (Capetownetc, 2018).

Water tax bills have been pushed up to an extent under extreme conditions, which appears to be an important driver for several strikes in Cape Town (van Heerden, 2018). A statement on this drought tax has made by the city: “It is a temporary, yet necessary measure, subject to the rainfall and dam levels. It will be implemented for the next three years, from 1 February 2018, until the dam levels have sufficiently increased," the city says on its website (capetown.gov, 2018).

3.3.1 Behavioral short-term change through demand management

Through rules, tariffs and regulations, the government has succeeded to surpass the due date for 'Day Zero' in the year 2018. Price elasticity, tariffs and social consciousness led to a reduction of as much as 50% of the water use (Figure 4), which allowed the city to hold up the Level 6B restriction until the rain season, starting around May.

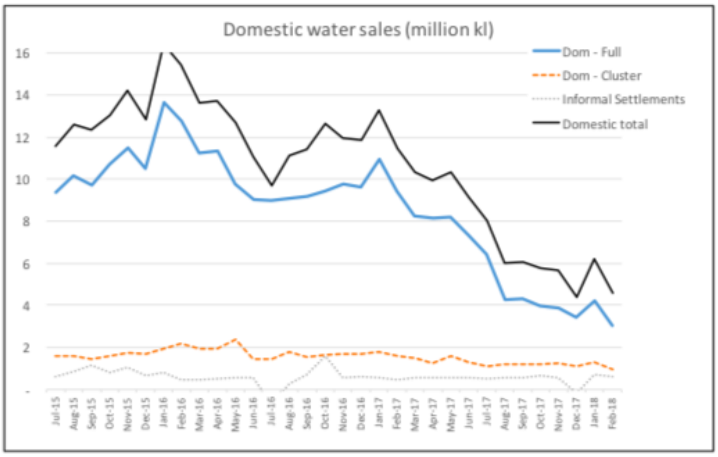


FIGURE 4. WATER DEMAND IN CAPE TOWN (2015-2018). SOURCE: (CSAG, 2018)

On a short-term emergency reduction, the restrictions have proven to be effective. However, these solutions are regarded to be of temporary nature; a long-term assurance of supply is needed to keep the population content and to cope with projected population growth. Currently, the assurance of supply is set at 1:50 (1 system failure in an occurrence sample of 50) by the CCT (GreenCape, 2018b). In the draught of 2016-2018 this assurance level has not reached the critical threshold for three years in a row. Although a rather unique event, with current projections it is ought to ensure a higher assurance of supply, to prevent these undesirable situations from reoccurring. Therefore, in the CTWRP, the government tends to focus on the creation of the new infrastructure in the supply side.

3.4 Supply management in Cape Town

The government is putting a majority at work in an effort to find new water as soon as possible, with risk for the environment involved; for example, ecologists warn that the CCT should proceed with severe caution as it continues to drill for an aquifer in the vicinity of the Steenbras Dam. The dam falls under the Kogelberg Nature Reserve, which is a part of the Cape Floral Region (Capetownetc, 2018). This region has been identified as one of the world's 18 biodiversity hot spots (TheSouthAfrican, 2018).

The City's Chief Resilience Officer (CRO) forecasts that "up to R2 billion rand will be spent on capital projects during the current and next financial year, while an amount of R1.3 billion has been projected as the operating costs to supply this water" (capetown.gov, 2018).

Quoting the City further, the conclusion was that "there are numerous other initiatives related to household and business adaptation that are under way which will be announced in due course. The strategic phase includes a number of initiatives, such as improving efficiencies in the Western Cape Water Supply System, rehabilitation of catchments outside of Cape Town's jurisdiction, and improved management and use of storm-water. The water resilience approach has both short- and long-term ambitions" (capetown.gov, 2018).

As water demands continue to grow and dams within the Cape region are almost reaching their limit capacity (whereas the only possibility for expansion is the dam in the Voelvlei catchment, adding another 200 Megaliters per day to the water supply (Du Plessis, 2018)), the CCT is one of the South African coastal cities that are considering augmentation programs as a potential future water supply source in the CTWRP. Within the supply mix, one can manage water through infrastructural enhancements in groundwater extraction, water re-use, storm water harvesting or desalination. The goal of the government in their so-called Western Cape Water Supply System Plan (WC/WSS, Table 4) on the long run, is to augment up to 350 million liters of water per day, whilst maintaining low water prices and preserving the natural environment (GreenCape, 2018b). The CTWRP was updated and adapted by the CCT and DWS (DWS, 2014), outlining the use of four forms of augmentation: (1) river to dam inter-basin transfer, (2) deep aquifer groundwater for bulk water supply, (3) shallow aquifer storage of recycled waste- and storm water, and (4) desalination.

TABLE 4: WESTERN CAPE WATER SUPPLY SYSTEM PLAN , 'WC/WSS' (DWS, 2013).

TECHNOLOGY	TOTAL ML/DAY PER TECHNOLOGY	POSSIBLE LOCATIONS
IMMEDIATE AND FIRST TRANCHE		
GROUNDWATER EXTRACTION	100	Atlantis and Silverstroom, Cape Flats, Table Mountain Group, Hottentots Holland
	SECOND TRENCHE	
WATER REUSE	70	Zandvliet Wastewater Treatment Works, Bellville Wastewater Treatment Works, Fisantekraal Wastewater Treatment Works, Potsdam Wastewater Treatment Works, Cape Flats Wastewater Treatment Works, Macassar Wastewater Treatment Works
DESALINATION – LAND-BASED PERMANENT	20	Koeberg, Silverstroom, Woodbridge Island, Granger Bay, Hout Bay, Red Hill, Strandfontein, Monwabisi, Harmony Park
	EXTREME TRENCHE	
DESALINATION – MARINE-BASED	100	Cape Town Harbour Gordons Bay, Koeberg
TOTAL	350	

This water resilience plan is still in its exploratory stages. Implementing either of these augmentation structures would inevitably take time (Figure 5) and would have a significant impact on water costing in the CCT (Figure 6).

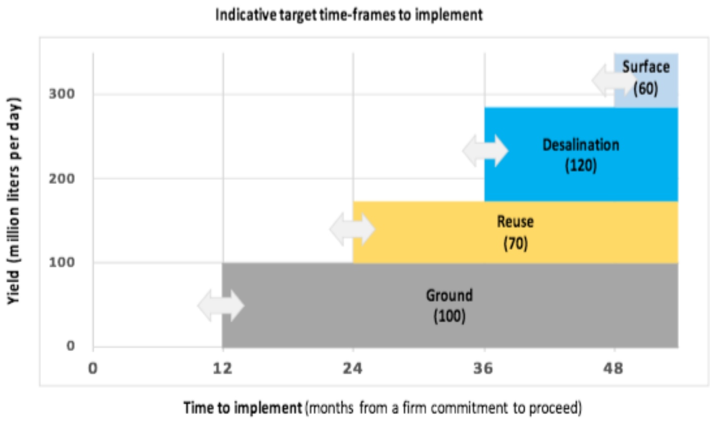


FIGURE 5. IMPLEMENTATION TIMES OF THE VARIOUS OPTIONS OF AUGMENTATION IN THE CCT (GREENCAPE, 2018 B)

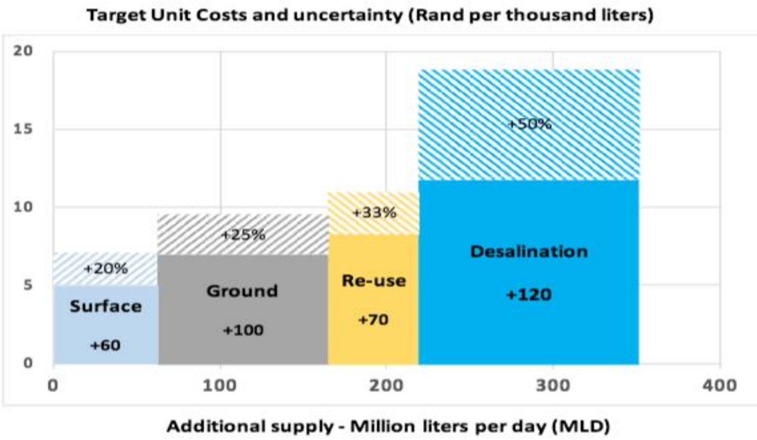


FIGURE 6. IMPLEMENTATION COST OF THE VARIOUS OPTIONS OF AUGMENTATION IN THE CCT (GREENCAPE, 2018 B)

Both GDP and limited budget (whereas the city adopts the term of economic water scarcity to justify their lack of implementation of the last decade (Cape Town Government, 2017) restrict the government of South Africa to invest more in water augmentation than is needed. The government needs to prioritize its needs to the - arguably- most critical cases in South Africa (for example urban development, crime). As gross domestic product of South Africa does not allow for much extra costing, investing in more augmentation structures could become obsolete, becoming a liability and putting an unnecessary burden on the socio-economic situation of the CCT. A equivalent example to illustrate this is the 15 ML desalination plant in Mossel Bay, Western Cape. Here, the government constructed a desalination plant that, after a critical situation in 2010, has not been used since. The mothballing of the desalination plant was a result of bad timing and no financial funds to keep the plant running.

Figure 7 Shows the system yield with the implementation of the CWTRO, whereas two scenarios are being accounted for: a high growth of population and low growth of population (3.38% and 2.3% per annum respectively).

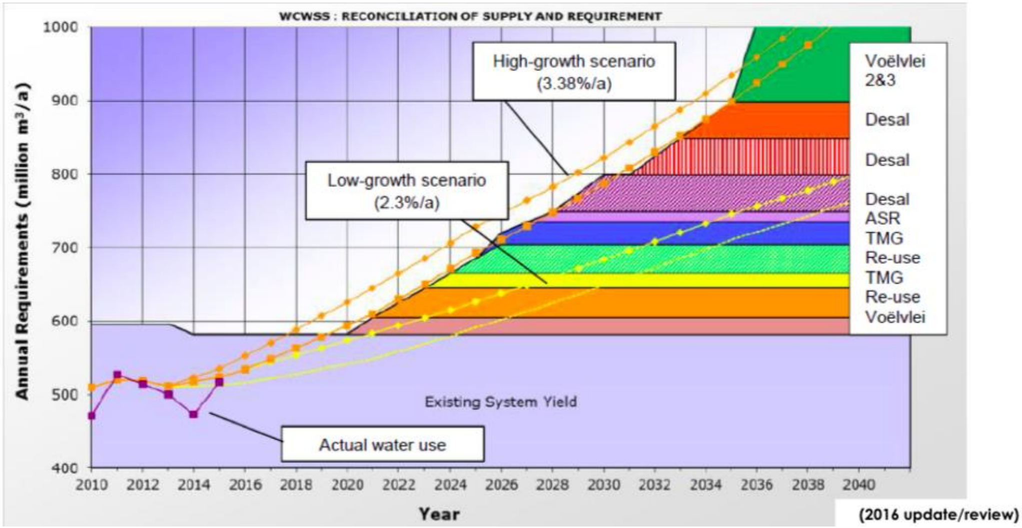


FIGURE 7. SYSTEM YIELD OF THE WATER RESILIENCE PLAN CCT (GREENCAPE, 2018B)

3.5 Augmentation possibilities for the CCT

Within the CCT, multiple augmentation possibilities are at hand for the government to implement. An extensive overview of these options on the supply side is given below.

3.5.1 Groundwater extraction

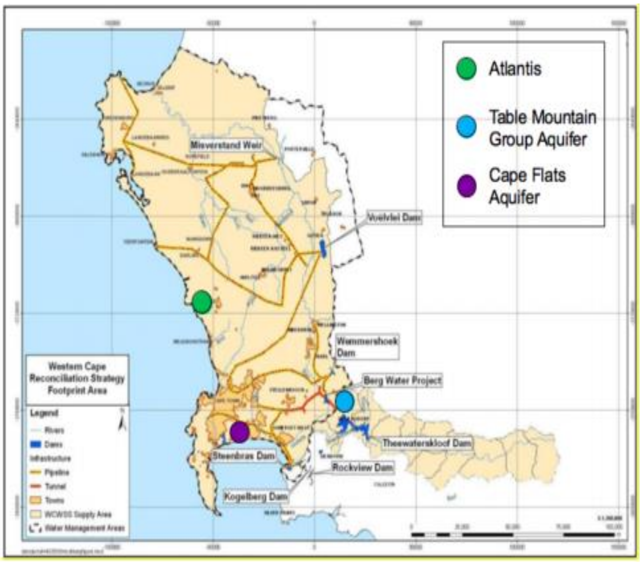


FIGURE 8. POTENTIAL GROUNDWATER EXTRACTION AQUIFERS WITH DAM WATER PIPES. (LUKER, 2017)

The CCT has a total of three large aquifers which could function as a potential groundwater augmentation source - the Atlantis aquifer (ATL), the Table Mountain Group Aquifer (TMG) and the Cape Flats Aquifer (CFA) as to be seen in Figure 8. In current situations, groundwater makes up 1.5% of bulk water sources from the WCWSS. Most of this water is the supplier of the village of Atlantis, a village with around 70.000 people (CityPopulation, 2011) whereas a groundwater scheme has already been implemented as matter of the experiment 'Managed Aquifer Recharge Scheme' (DWS, 2010) in this village.

In comparison with the other aquifers TMG and CFA, the ATL is relatively small in its supply. Feasibility of groundwater aquifers is considered through the state of the aquifer, recharge levels and its relative cost – inferred by the pumping cost involved of reaching the bulk water. In the context of the CCT, feasibility studies show that the best option at hand would be the TMG. Reasoning for this can be found in the relative pumping distance (the water in the aquifer is located at around 2-3.5 meters whereas water of CFA and ATL sit at respectively 8-9 and 10-11 meters. The TMG aquifer is estimated to hold a potential annual yield of around 100 million m3 (Colvin & Saayman, 2007), equivalent to around 25% of the CCT's annual water consumption. The recharge rate of the TMG is estimated to be around 7.5-20% of the mean annual precipitation. This evidence is supported by field research done by Yi (2016). In terms of demographics: the TMG is located in a riparian, isolated area close to the largest dam of the CCT, holding around 55% of its annual water supplies - the Theewaterskloof dam. This directly causes a voice of environment to be regarded; biologists argue that the survival of the TMG is critical for the survival of the river runoff to Theewaterskloof (DeClerq, 2018). In current plans of the WC/WSM, the government aims for an extra 150 ML/D in augmentation through groundwater supply (GreenCape, 2018b).

3.5.2 Water re-use

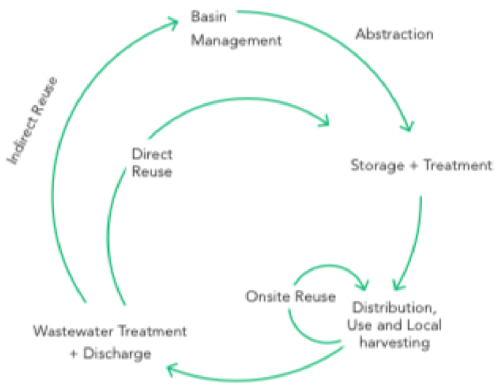


FIGURE 9: SCALES OF WATER RE-USE (GREENCAPE, 2018 A)

Several opportunities in urban markets are nowadays existing that reduce the water consumption. Water reuse can occur on a variety of scales, dependent on its intended use (Figure 9).

In the CCT, GreenCape (2018a) states that most of the water reuse is to be won in concentrated, high intensity water users; this is common within the industrial sector, representing around 115 billion rand of the water industry, equivalent to around 10% of the total water consumption (Quantec, 2017). According to GreenCape's market intelligence report (2018a), opportunities for the industrial sector lie within both the installment of new treatment systems and the upgrading of treated effluent systems.

Several companies are increasingly investigating their water reuse streams. Multiple industries in South Africa already re-use large amounts of wastewater, especially within the mining sector; yet, none has claimed to have achieved full re-use (GreenCape, 2018a).

Treated effluent, a more distinct term for wastewater from municipal treatment works that has been treated through process, is becoming an increasingly interesting source of re-used water for the industrial sector (GreenCape, 2018a). Nevertheless, to process the quality standards to be used on-site in an industrial setting, the treated effluent needs to be upgraded – creating an opportunity for water treatment companies in the CCT. For most of the large industrial users in Saldanha Bay, the product of upgraded effluent water is already implemented. The CCT still lags behind in these developments. In current plans of the WC/WSM, the government aims for an extra 70-90 ML/D in augmentation through water re-use (GreenCape, 2018a).

3.5.3 Desalination

In current plans, the government is considering adding an extra 120-150 ML/D to the supply mix in the form of desalinated water (Cape Town Government, 2017; GreenCape, 2018b). This number is considered to be optimal as a larger number of desalinated supply might backfire on the population and become a financial burden to the socio-economic situation (R. Kruger, 2018; GreenCape, 2018a). Demographically, desalination seems a right fit for the CCT as it is a city located by the sea. At current times, only temporary desalination plants have been installed in the CCT, accumulating to a total of 7 ML per day. In the whole of Southern Africa, as of today a total of four permanent desalination plants are known to be installed using the RO technique, of which the largest installed capacity of desalinated water is the one in Mossel bay with a capacity of 15 ML/d.

Additionally, the government is proposing a single desalination plant of 150 megaliters for augmentation. The proposed desalination site is yet to be revealed: the reason for this is unknown, but experts guess that is has to do with either contracting or the environmental opposition, as prematurely revealing a site might startle environmentalists for the brine discharge (Winter, 2018; DeClerq, 2018).

3.6 System exploration

As this water renewal program is being proposed, up until now a holistic, integrated overview of obstacles and bottlenecks on the system has not yet been released by the government, and is therefore necessary to conduct. The water system is one with specific interdependencies related to the city; To merely formally adapt an analysis on water systems to the CCT would not justify specific connections (take for example the amounts of unauthorized boreholes being implemented by individuals from the society). Therefore, a new system capturing the whole of the water supply and demand system should be analyzed for the CCT specifically. This could function as the ‘overall problem spectrum’, which is meant to be the overall picture of the water supply and demand. After completing a solid representation of this water system, possibilities to expand will be created as the method of system dynamics can operate on multiple scales at once. It is necessary to have this spectral overview for conducting the more specific investigation on an exploration of an addition to the water supply and demand mix; this provides a common ground where one could exactly see how the certain investigated augmentation matter would affect this ‘bigger picture’.

3.6.1 Case study specific exploration

This research chooses to focus on desalination as this is different to conventional surface and groundwater supply sources in that it is climate-resilient, having an assurance of supply of essentially 100 percent (Blersch & Du Plessis, 2014). However, the increased reliability comes at a cost. Within the framing of sustainable development, this research explores the multiple costs and benefits in their interdependent forms:

1. The financial cost of installing a permanent desalination plant using reverse osmosis (RO) is projected to cost around R2 Billion, excluding variable cost once the plant is operational. The SD model will provide an exploratory analysis on the uncertainties regarding new developments, (developments in) brine dispersion and its associated environmental costing.
2. Possible socio-economic impacts; the effects on demand of increased water pricing.
3. Environmental impacts: desalination plants produce by-products that can be harmful to sensitive marine ecosystems. RO is also an energy-intensive process with associated greenhouse gas emissions.

In the research of Joubert et al. (2003), a multi-criteria analysis with multiple water expert groups in the CCT has been performed. Sentiment showed the importance of finance (particularly the unit reference value with an assessed (rescaled) weight of 0.152 and tariff change 0.144), the importance of the socio-economic situation (with health and employment assigned as respectively 0.096 and 0.048) and the importance of environment (0.053 for estuary) on water augmentation. Accordingly, this research tends to provide insight on this sentiment of apparent importance.

Since desalination is an intersectional complex issue, intersectional expert input is needed to capture the behavior with the right reasoning. Therefore, in collaboration with various stakeholders by institutes at the University of Cape Town, Stellenbosch University, water management groups, consultants, and other affected individuals, over the period of April 2018 to June 2018 the ACTDesal model[2] on the water supply and demand system of Cape Town was created; zooming in towards the exploration of implementing desalination into this system for the period of 2006 until 2056. For quantification and structure, this model builds on previous conducted research both SD related (Musango et al., 2016) and non-SD related research (Blersch & Du Plessis, 2017; Arafat et al., 2017).

3.7 Choice of desalination technique

To provide a holistic picture of possibilities in desalination, a broad overview of the most relevant processes is provided, together with the positive and negative points about each method.

3.7.1 Vacuum distillation

The most traditional method is the method of vacuum distillation. Essentially, this method comes down to boiling the water to extract impurities. Under vacuum, water only needs to be heated to 70 degrees Celsius to boil and extract freshwater without unwanted elements. Overall, water distillation is reasonably cheap, and the extracted water can be reused, whereas most installed plants still maintain this traditional way of desalination as their budget does not allow for a reinvestment to new water plants. Nevertheless, some of the unwanted elements may be found in the distilled water. Additionally, when distillation is done on a larger scale, a large amount of energy is needed. The distilled water does not contain any oxygen and is considered to be very tasteless, and subsequently contains very high levels of acidity.

3.7.2 Solar humidification-dehumidification

Another method to consider is solar humidification - dehumidification: it is a technique that 'mimics' the natural water cycle on a smaller frame, evaporating and condensing water in order to separate from other substances through thermal energy. Thermal energy would produce water vapor on saltwater, later to be condensed in a different chamber (Gómez-Camacho & Carlos, 2002). A major advantage is the sole use of solar energy for this method, although it requires large amounts of space to do so for large-scale desalination. It is relatively inexpensive, although there should be a reliable and consistent source of sunlight.

[2] Assessment of Cape Town Desalination, the in-depth analysis of desalination as part of the ACTWater (Assessment of Cape Town Water) project

3.7.3 Reverse Osmosis

The current trend in water desalination in terms of yearly growth and increasing installed capacity is a chemical method called Reverse Osmosis (RO). Essentially, an applied pressure is used to overcome so-called osmotic pressure, which in simple terms are the bacteria residing in the water at certain pressure levels. RO has the ability to extract different sources of water as all water has different bacteria levels. RO does not allow ions or large molecules to surpass the pressure points but does allow smaller molecular components (the H2O) to pass freely. Major advantages can be found in the purity of the water; RO is shown to be the *most effective* method for water softening of current times (Biotech, 2016). Also, the process has a simple maintenance; the operation can be optimized with the machine still running. Nevertheless, since the method does not allow large molecules to surpass, the water is demineralized since these elements cannot surpass as well, basically leaving the water with acidity. Also, a large amount of power is required for a RO plant, which usually comes involved with major set-up costs. As a result of RO, the non-usable parts of the saltwater would become a source of waste, which then would be chemically burned, which in turn is bad for the environment.

In this research, parameters have been set to the RO technique. This is partially because this is the most favored technique nowadays as this is the ‘cheapest’ way of producing desalinated water. Specifically for South Africa this would play out well since South Africa is rich in coal energy; therefore, it would become reasonably cheap for the county to provide the required energy. A third factor involved is the expertise available in South Africa; the country does not have the resources to continually gain foreign expertise on the maintenance of the RO plants and is in the effort of reducing their unemployment rate which is currently on 30%. It would require a certain degree of knowledge to put their own people at work, whereas all plants currently produced in South Africa are using the RO technique; hence, the choice of implementing the RO technique seems to be the most viable option (Winter, 2018; Du Plessis, 2018).

3.8 Advantages and disadvantages of desalination

First, a major advantage of water desalination as a whole is that it provides accessible drinking water where no natural supply of any kind of potable water exists. In terms of Cape Town, this translates into the enormous occurrence of drought over the last years; therefore, there is very little natural water supply available, caught by the rainwater dams. Desalination can provide a possible water source, especially as Cape Town is located near the sea which would allow for saltwater to be directly harvested to avoid large transportation costs involved.

Secondly, water desalination might conserve habitats that are mostly rich on biodiversity. As natural freshwater supplies are mostly located in areas that need protecting (in Cape Town, one can look at national parks – the dams are located near natural reserves as Houtberg and the Hawekwa national reserve), water desalination can prevent from building more dams in these areas and thus destroying the natural habitats of endangered species. Equivalently, desalination can take the stress of the extraction of groundwater reserves, which can be detrimental for the surrounding land environment.

Subsequently, desalination has possible negative impact on the environment in itself. Whereas it is considered reasonably healthy for land environment, brine discharge of a desalination plant is considered dangerous for the marine environment. For the production of 1 million liters of desalinated water, one requires a total of 2.5 million liters of seawater. After treatment, 1.5 million liters of this water is to be poured back into the sea without any nutrients, so-called brine water. Several correlations have been found in the premature death of fish species in the areas where this brine resides (Raventos et al., 2006; Danoun, 2007; Bleninger & Jirga, 2008), making the desalination plant a possible danger to the marine environment. As stated by Dr. Winter (2018), attempts to reduce or even completely deplete brine discharge are still in their viability stages. For example, research from Williams et al. (2015) is testing the possibility of composing brine discharge into a crystallized form, essentially possibly pushing back the discharge to zero; nevertheless, this research is still a work in progress.

The largest disadvantage, especially with the budget available by the government, is one of financing. It is a major cost for a government to build and operate desalination plants. Depending on their location, building a plant of around 100 megaliters can range from R. 1.5 billion to R. 2.9 billion (Arafat et al., 2017). Once operational, plants require huge amounts of energy. Energy costs account for around 60% of the total cost of producing desalinated water.

3.9 Obstacles to desalination in the City of Cape Town

The first obstacle is cost: today's desalting plants are hundreds of millions of dollar-projects, and it will take time for improving technology to bring the cost down. Timid government politicians and officials are already delaying action for years, during which plant costs and related distribution facilities might double or even triple. Within the Cape Region, it is proposed that a plant would cost around 1.5 - 2.1 billion Rand (equivalent to ~$120M-$155M in current conversion rates) to install (TheSouthAfrican, 2018). When the plant is installed, operational costs remain – a desalination plant is known to be highly energy intensive. Operational costs (mainly through energy) and maintenance cost would be a constant burden on the government.

Secondly, resistance in the environmental sector is not to be disregarded. The potential impact of brine residue might be a serious obstacle as opposition from environmental organizations can issue a halt in case the EIA proposal is considered to have a too heavy impact on the marine environment.

Thirdly, a socioeconomic risk is involved: the risk of the cost of water reaching a level sufficiently high to have significant effects on the cost of living and doing business in the Cape region – an undesirable socioeconomic situation. Though the cost of water to consumers might be different from the unit cost of producing water due to government tariffs, at national level the cost of water production would evidently affect the socioeconomic well-being of a country. (Van Minh, 2011)

Last, installing a desalination plant can take up to two years from construction to finish. Including the process from the very beginning (getting permission, making an environmental impact analysis) a proposed plant can take up to three years to be established. In terms of space, a company would be needing around 25 acres of land (Arafat et al., 2017), which might be problematic as one is dealing with a metropolitan area – the longer the pipelines have to be as the plant needs sufficient space, the more costs are involved.

All in all, large investments are required to the water supply system and its related water resources (conventional as well as alternative water resources) ex ante and therefore it is a proposal is needed to overcome the challenges in a viable way by conducting a study on the water supply system on a long-term perspective. Nevertheless, uncertainties regarding the environment arise by scoping to a long-term time frame.

3.10 Uncertainties

The present study period of the water supply system of Cape Town spans 50 years from 2006 to 2056, with a time step of one year. Inevitably, over the course of this time horizon, the environment the water supply system changes in ways that are not yet to be foreseen. Reports indicate the price of desalination to have fallen over the years (Zhou & Tol, 2005), although to what extent these costs will drop is yet still unknown.

Also, it is not yet clear to what extent population will grow and its expanding urban water demand through the years. On the supply side, the amount of rainfall throughout the years to replenish the dams remains highly uncertain through rainfall variability whereas a scenario analysis is required. Should there be a large rainfall constantly throughout the years, then the desalination protocol might render to be a waste of money. Should there be no rainfall at all, then most extreme measures should be considered as the dams would drop to zero.

The current trend in desalination is mostly based on a RO process which is highly energy-intensive and therefore subject to energy prices which are highly volatile. Lastly, the demand for water in Cape Town over the time horizon of 40 years remains an open question. The uncertainties are therefore twofold in the water supply system of Cape Town (in line with Zhang & Babovic, 2012):

1. *uncertainties which are associated with the capacity of the water supply*

2. *uncertainties which are associated with the costing of the water supply.*

To address these uncertainties, an attempt on internalizing the system and capture its behavior over time, and simulate consequences in a safe environment should be made with the method of System Dynamics.

4. Method

4.1 Research framework

The System Dynamics model finds its theoretical framework in the conceptualization of Slinger et al. (2008), as to be seen in Figure 10.

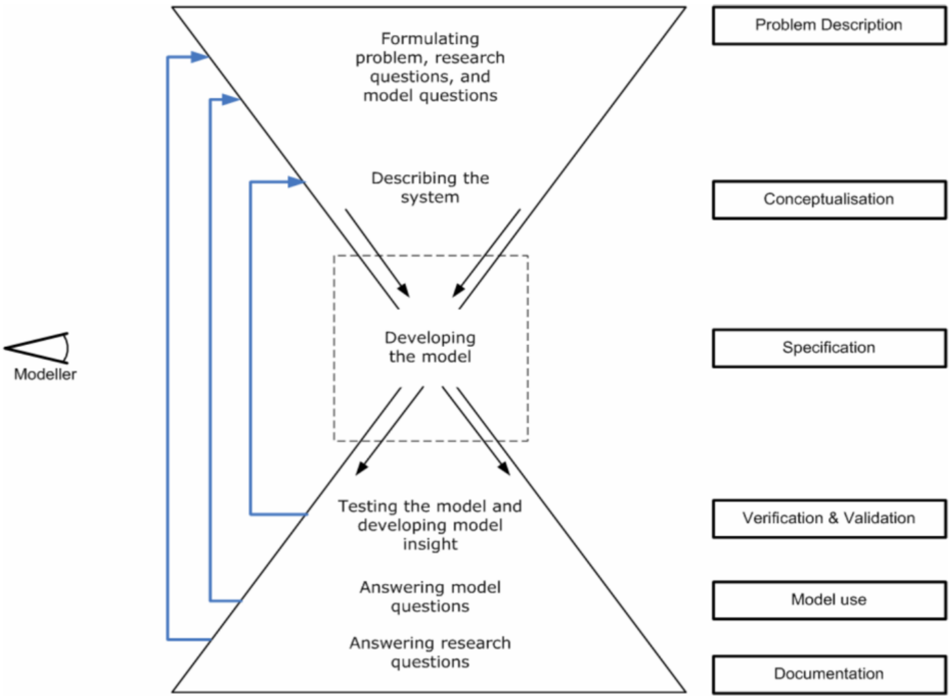


FIGURE 10: THEORETICAL FRAMEWORK FOR THE CASE STUDY (SLINGER ET AL., 2008)

In the problem description phase, the research had been put subject to a preliminary case-specific literature study. Afterwards, the problem was conceptualized and specified with guidance of in-depth interviews with experts. For verification purposes, a second round has been implemented in conversation with stakeholders. The model has been tested in various ways, and documented accordingly.

4.1.1 Research design

The research was designed to go through a total of three phases, from start to completion. Preliminary research was conducted from the period of February until April 2018, whereas practices as a preliminary literature review, boundary setting and stakeholder scoping took place. Afterwards, a 10-week period of dedicated fieldwork commenced in Cape Town, South Africa. Within this period an intensive number of interviews were held, with the attempt to establish a model in conversation. Interviewees were selected through specific relevance to the model. To achieve new input from other sources, a snowball method was used, starting with the host University - the University of Cape Town (UCT). Through Dr. Kevin Winter, multiple other stakeholders of various fields were addressed. The in-depth interviews were all ranging around 2 to 3 hours. Finally, the model had been conceived in Stella Architect and stakeholders were asked to comply with the model as a form of validation. A schematic overview is given in Figure 11.

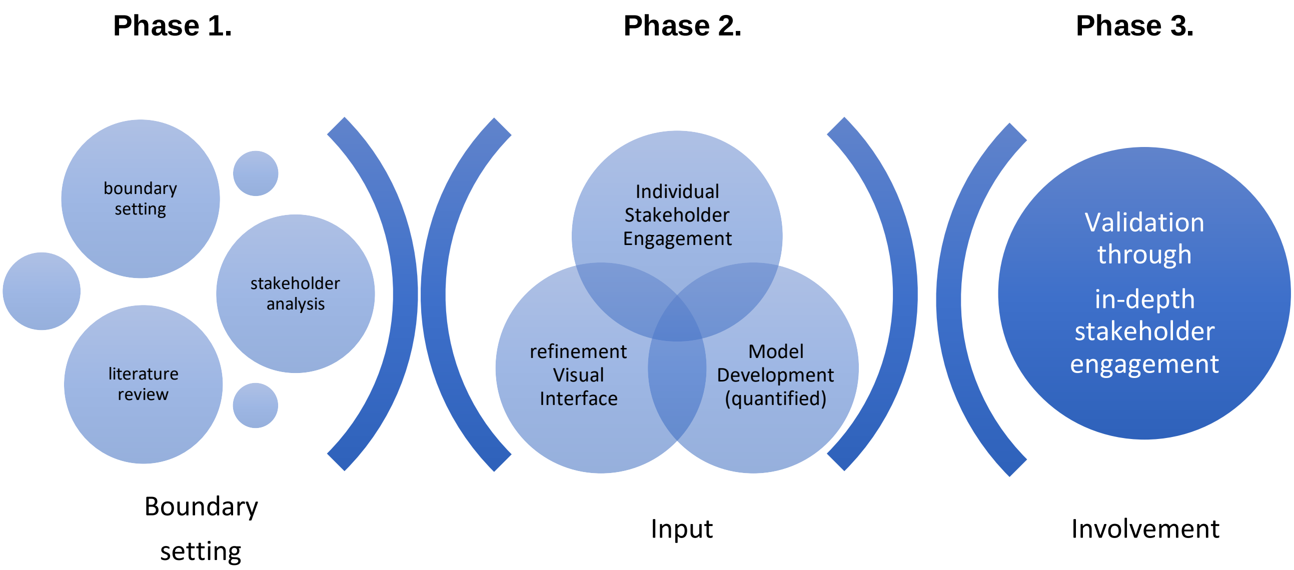


FIGURE 11. SCHEMATIC OVERVIEW OF THE MODELLING PROCESS

4.2 Phase 1: Case-specific literature

For problem description, a preliminary literature study has been done. The leading document for extracting quantifications and finding arguments, delay times and central decision-making was the Water Outlook Report (GreenCape, 2018b): a monthly updated report issued by the GreenCape, rich of up-to-date information and monitoring on the drought. Rainfall patterns were taken from the Climate System Analysis Group, as this was argued to have the most accurate numbers by UCT and Stellenbosch University. This research builds on work from Musango et al. (2016) for conceptualization of the model as this Stellenbosch-based research group uses systemic analysis for a similar problem in the Western Cape, the water-food-energy nexus. In calculating Unit Reference Values (URV's), the method of Blersch and Du Plessis (2014) was utilized. A large body of conceptualization is taken from the book: '*Desalination Sustainability: a multinational contribution'* under the lead of H. Arafat (2017). This book describes multiple concepts of finances, environmental impacts and socio-economic levers in detail and was therefore considered useful for analysis. For the marine environment, a GIS mapping has been utilized from the freely available CCT marine ecosystem map (egis.gov, 2018). A diverse range of other reports, case studies and theses were used for the quantification of the model, which will be more described in the model reporting.

4.3 Phase 2: Specification – Interviews

The interviews were held in the period from April to June, predominantly in the Cape Region. This subchapter describes the process of selection, followed by the interview procedure and the elements for stakeholder engagement.

4.3.1 Stakeholder selection

Stakeholder selection has been performed in the guidelines of Reed et al. (2009); first, the context has been defined, followed by the 'getting to know stakeholders' phase – which mostly inferred a snowball method. Lastly, a rather continuous attempt to develop stakeholder engagement was made through the creation of the interface. Stakeholders were ultimately selected accounting for the apparent power, legitimacy and urgency in their own expertise (Mitchell et al., 1997).

Firstly, to get a broad picture of the overall CCT water supply and demand system, the researchers had multiple conversations for the sake of conceptualization with the director of the Future Water Institute at the University of Cape Town, Dr. K. Winter. On the hand of these conversations, the model gained its primary structure of water supply. After gaining this insight, contact was made with Stellenbosch University, providing more of the technical holistic overview of the water supply system by the director of the Stellenbosch University Water Institute (SUWI), Dr. W. De Clerq. The model deemed a qualitative representation from a socio-economic perspective necessary. Therefore, after a series of emails to possible contacts on the demand side of the water spectrum, interviews were held with both the GreenCape which is a regional Non-Governmental Organisation (NGO) concerning the sustainability of the CCT, and a representative of the civil rights group Water4CapeTown.

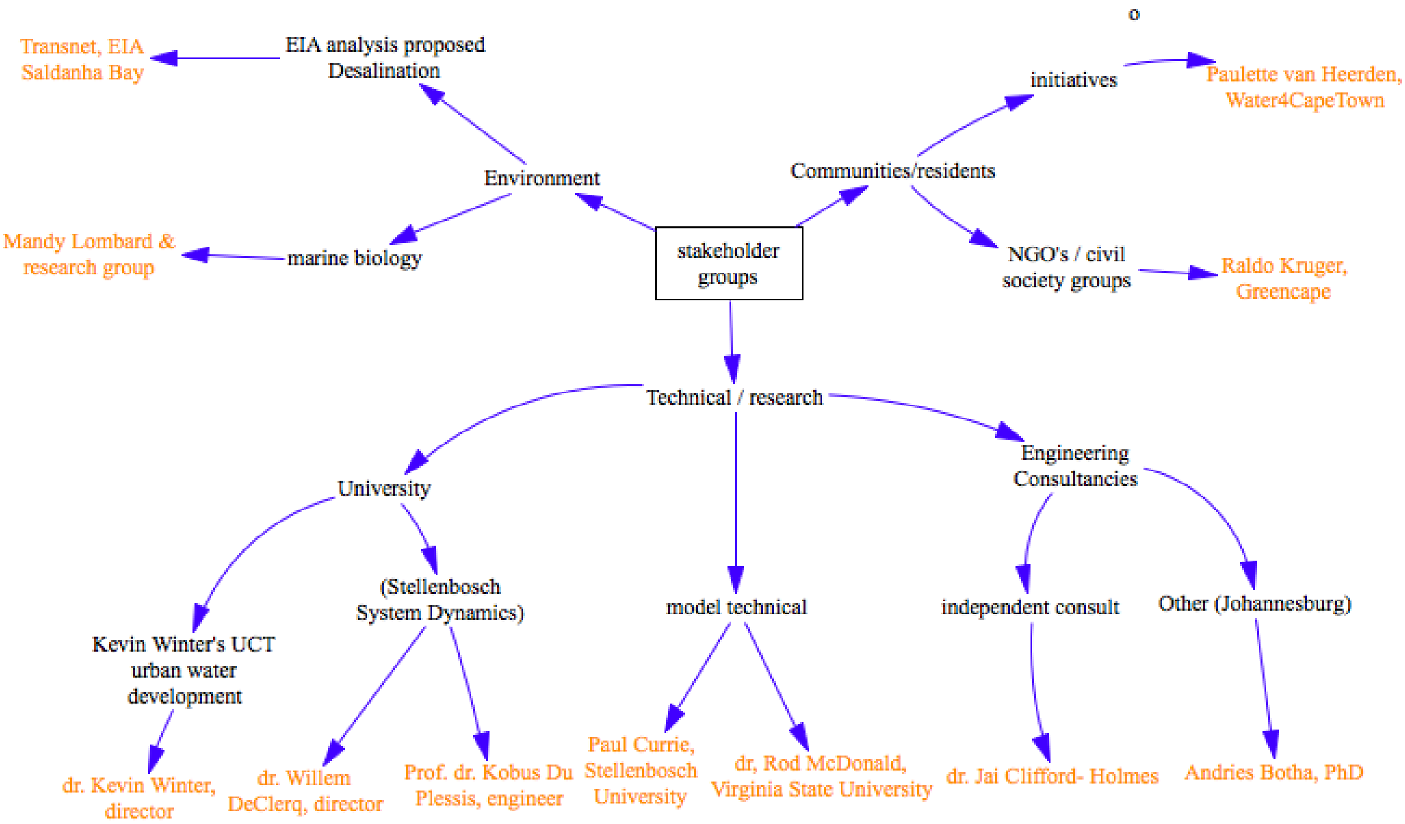


FIGURE 12: TOTAL STAKEHOLDER ANALYSIS ACTDESAL

Diving deeper into desalination resulted in the need of an enhanced insight of the marine biology expertise, which was structured through spending a week with several marine biologists in a System Dynamics short course and multiple conversations with Prof. Dr. M. Lombard. For technical aspects of costing, a conversation with the author of the article about the CCT desalination possibilities and its associated URV, Prof. Dr. K. Du Plessis, gained useful structuring to the model. For input on the demand side, a conversation was held with the NGO's GreenCape and Water4CapeTown, represented by R. Kruger and P. van Heerden. Furthermore, in provision of technical help and model structure, input was provided by P. Currie who is a postdoctoral fellow in water systems of the Stellenbosch University, together with Dr. A. Botha - a well-respected senior entrepreneur on System Dynamics -, a senior lecturer in System Dynamics of Virginia State University, Dr. R. McDonald and iSee Systems' programmer B. Schoenberg. In Annex II A, the most relevant points of each stakeholders are noted in a table, whereas Figure 12 gives a schematic overview of the stakeholders involved. Furthermore, a complete planning of the project can be found in Annex II B. A full list of the choice of variables which were either critically endogenized, loosely endogenized or exogenized - together with the corresponding stakeholder(s) - can be found in Annex III A, which is a continuation of the most relevant points of stakeholders.

4.3.2 Interview procedure

In advance, the interviewees were sent a concept note (Annex III B.) of the project, accompanied by a Prezi presentation. The Prezi presentation was further explained in the conversation, a 20-minute monologue stating the problem, boundaries, approach, procedure, a small introduction to the method of System Dynamics, the model itself, a demonstration of the interface and the possibilities for the stakeholders to contribute to the model. All of the interviewees were asked a specific contribution from their expertise or field, and were explained how the research found them suitable to contribute. In case the participants had further questions or inquiries, a 7-page concept note (Annex IV.) has been created explaining the method of System Dynamics in relation to the project further, together with the process of the fieldwork stage.

4.3.4 Stakeholder engagement and visualization

In line with the guidelines to stakeholder involvement of Bryson (2004), for the sake of clarification and visualization to the stakeholders two models were created; firstly, a small concise model containing only the most essential dynamics of the behavior, and a larger, more detailed model. In the interface - which is an option to visualize a created model in Stella Architect (shown in Annex V.) - the stakeholders were shown the small model, a written line of argument about this model through a storyline under the button ‘total model’ on the homepage of the interface and a corresponding comparative graphical representation that was created for this smaller quantified model. In this graphical representation, the stakeholders had the option to increase and decrease multiple levers – comparative graphs were shown of multiple critical variables, as to be seen in Annex V. It was made clear that the results were corresponding to an abstract-level model whereas stakeholders could come in with input for the larger model. In the interface, the larger and more detailed model was represented in the other storylines under the buttons ‘finance’, ‘water pricing’, ‘supply’ and ‘demand’.

4.4 Phase 3: Modelling framework

To provide an initial line of thought of the structure of the model, Figure 13 provides a top-level overview of the sectors being analyzed in the model.

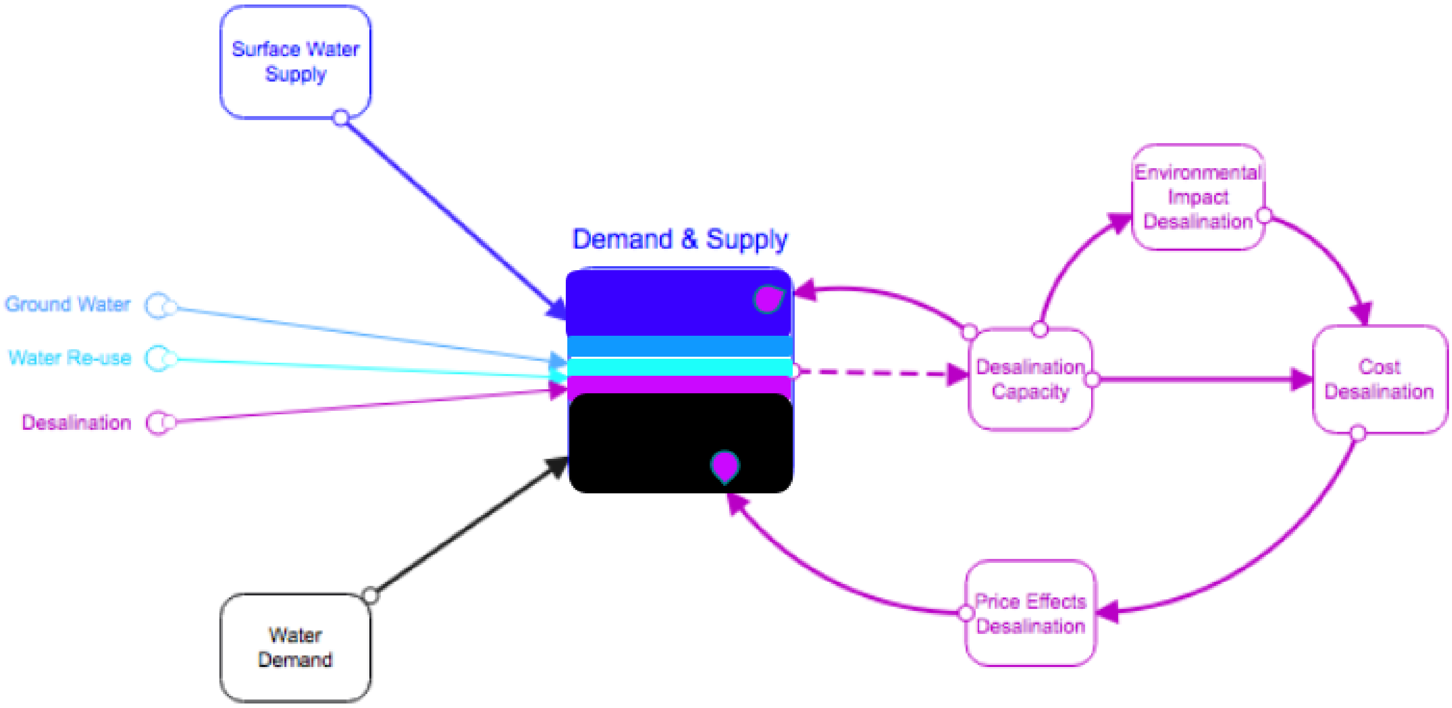


FIGURE 13: ACTDESAL FRAMEWORK

In the representation, the following reasoning is applied. From the water supply mix, consisting of normal and augmented supply, the capacity of desalination is depicted as central variable for exploration. Desalination capacity is captured by the interplay between water demand and water supply – resulting in pressure for the government to implement desalination. The higher the supply-demand gap, the more need for augmentation measures (or stricter water demand management), which is a reactive decision point for the government to consider desalination. Increased capacity on desalination would lead to an increase of installment- and operational costs of desalination.

Subsequently, the model explores the increase in brine dispersion in either the Benguela or the Aguillas coast, controlling for the harm it would do on the lifespan of pelagic fish species (the most abundant fish species in these regions). The model calculates an associated environmental cost accordingly, feeding into the total cost. On the basis of price elasticity the model calculates the result of an added water price for desalinated water to the water demand, which would lead to a lower water supply gap accordingly. In- depth sub-modelling and levers for change were included on the basis of shared insight whereas the model has been quantified on the basis of available data.

4.4.1 Model verification procedure

System Dynamics is a pseudo-science: every model is unique, and chances to reproduce the same model are small; the purpose and usability of the model however, finds a larger importance (Forrester, 1970). To pursue a strong model finds requirements in consensus. To make sure one generates the right behavior for the right reasons, multiple formal tests have been created for verification (Forrester & Senge, 1980). Validation builds confidence in a model; the more testing the model passes, the more valid the results are. However, this has been debated by Barlas (1996; 2007); difficulties arise mostly from a technical viewpoint when it comes to validation. Barlas claims that statistical treatment holds assumptions that they are serially independent, not cross-correlated and normally distributed – although in a model, one seeks to show 'no significant difference' in a model (as closely to reality as possible) which is contrasting with the rules in statistics.

Arguments aside, it is widely claimed that confidence in a System Dynamics model can be increased by a wide variety of tests – more an 'accumulation of confidence' (Barlas, 1996). Barlas subsequently provides an overview of the most relevant validation tests, to be found in Annex VIII. The overview suggests there are three types of validation that are essential for validating a model: Direct tests of model structure, Structure - oriented behavior tests and behavior pattern tests. The total amount of tests account to a number of 58, spread over the three categories.

Since there has hardly been done any monitoring on the water system of the CCT so far or numerical resources have not been publicly accessible, the model gains most of its verification through conversation with stakeholders. When data was not publicly available, the procedure was the following: through conversation with the experts of the determined field, a proxy was asked. In the form of a verification through consensus test the proxies were implemented in the model.

This model adapts multiple tests of all categories, whereas an extensive overview of the execution of the proposed validation tests and the results thereof are to be found in Annex VIII. In tests of model structure, which essentially are tests that assess structure and parameters directly, a structure verification test, a parameter verification test and a dimensional consistency test have been performed. The structure verification test was done by verifying with fellow modelers and experts whether the model represents the real system in multiple rounds of conversations. The parameter verification test (a test to argue whether the model has representable values) has, due to data limitations, been performed in the form of qualitative verification. Although most parameters which are present are being represented in such a way that there is small room for variance and outliers, parameters which were considered an ‘educated guess’ became subject to the mental model of multiple stakeholders – whereas an average of these values was taken for parametrization. In the dimensional consistency test the model was made unit consistent with the unit groups: Rand, Megaliters (ML) and Fish.

For tests of model behavior, which are tests that evaluate the adequacy of the model structure through analysis of behavior that is generated by the structure, the research performed a symptom generation test, an extreme policy test, and a behavior reproduction test. In the symptom generation test, which is a test showing that the model in the current situation leads to a problematic situation, a system failure is considered when water demand would govern the water availability stock (Annex VIII, Figure 1). In the extreme policy test, which answers the question whether the model behaves as expected with the alteration of a policy statement in an extreme way, the model is run under multiple extreme scenarios (the increase of augmentation measures by 3 times and the increase of government subsidies by 99% (Annex VIII, Figure 2 and 3). In the behavior reproduction test, which is a test against the subsequent reference mode of the model to adequately capture the adequacy in match to the model-generated behavior and the observed (real-world) behavior, the model was tested against both the historically available data (for example rainfall patterns, supply and demand over the years) and the ‘smaller’ model which was verified by the stakeholders to function as a reference mode. In Annex VIII, Figures 4, 5 and 6, the model shows the accuracy of the produced behavior of the most relevant variables to the reference mode.

For behavior pattern tests, which are essentially tests of policy implication (tests that attempt to verify that the response of a real system to a policy change would correspond on the response predicted by the model), the boundaries of the model show that performing these tests would overshoot he purpose of this exploratory model and can be subject to subjective interpretations. Therefore, the research chooses to avoid any form of policy implementation to the model.

5. Model & Results

5.1 Causal loop diagram

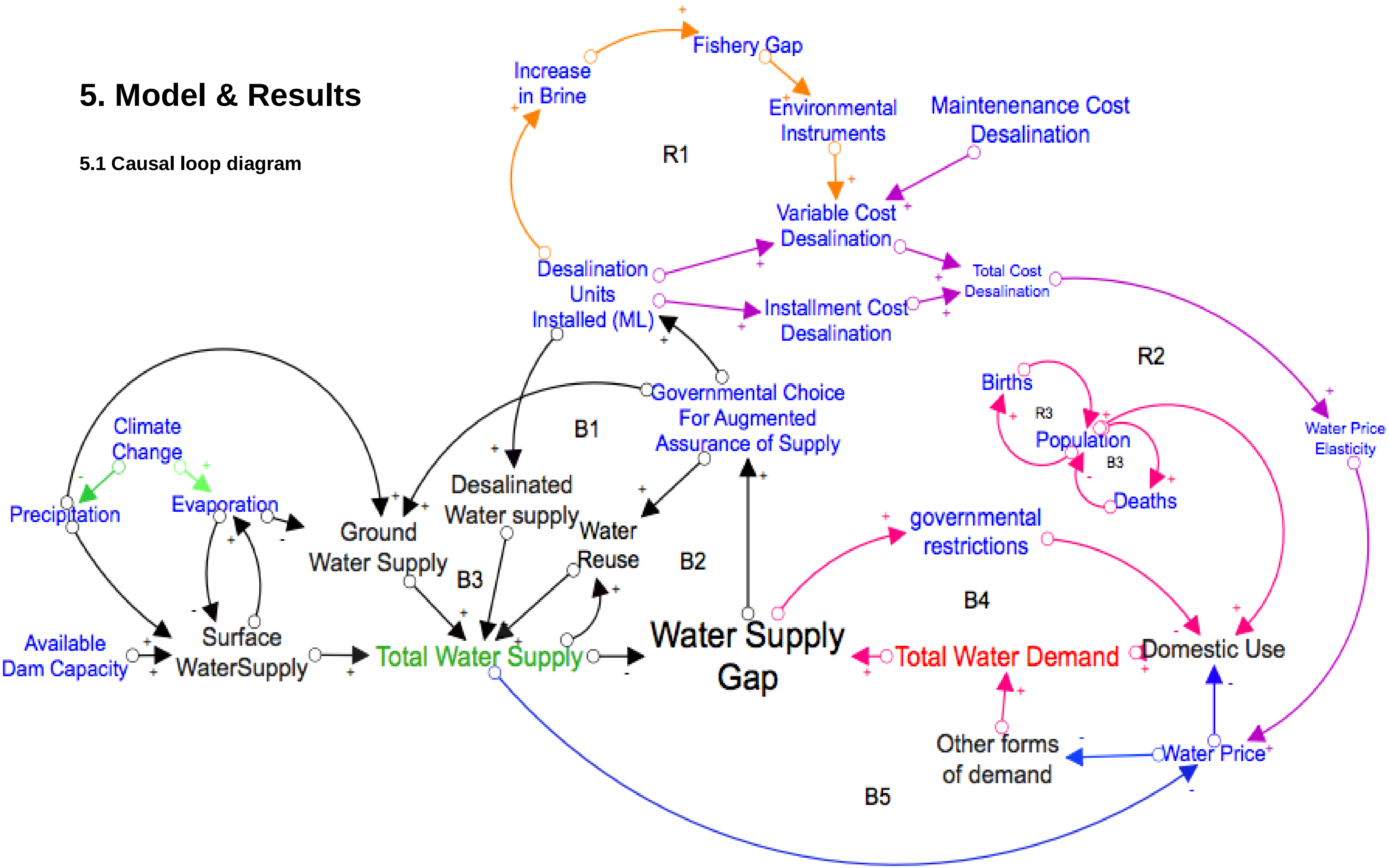


FIGURE 14: CAUSAL LOOP DIAGRAM OF ACTDESAL

To show the model in detail, a total overview of the model is given in the form of a Causal Loop Diagram (CLD) in Figure 14. A CLD is a representation of the system capturing the interrelationships between the multiple variables: indicated with either plus or minus, one can directly see the nature of the relationship with the interdependent variable. The CLD also captures feedback loops in the system. These loops, either reinforcing (R) or balancing (B) indicate the circulating behavior over time. Subsequently, this CLD (Figure 14) corresponds to the multiple quantified Stock and Flow Diagrams (SFD's, Annex VI). On a sector-by-sector basis, one could follow the line of argument:

Demand

Water demand is mostly being characterized as the population consuming the water provided by the water supply which is being calculated by the amount of births and deaths over time. In times of drought, the government needs emergency demand management, translating into restrictions being put up by the government. Another driver influencing demand is the water price. The more expensive water gets, the less water will be used.

Supply

Water supply is characterized by either surface water supply, groundwater supply, water reuse and desalinated water supply, whereas dam capacity is known to be the largest driving factor for water supply. The more precipitation through rainfall, the larger the dam flow for that year. The more water that evaporates (whereas climate change would contribute to more and more significantly with current predictions), the less surface water supply. This water supply is restricted to the total dam capacity, which is a large limiting factor in terms of Cape Town as dam capacity is almost reaching its limits. Equivalently, groundwater supply receives its water through the same precipitation of rainwater, corresponding to its area. Water re-use is calculated by the potential water to be 're-used' and its structures the government decides to build in response to the water gap; the more water is left from the water supply after the demand is fulfilled, the more water there is to be re-used. Lastly, desalinated water is a form of augmented supply feeding from the water gap.

The water gap

The gap is induced by the interplay of water demand and supply. When supply cannot suffice for the demand for that year, the system detects a water gap; water results to go in a 'backlog' to be fulfilled (to get the dams back to 100%). The situation as it is now is one of a reactive governance: only when the gap is visually present, the government is willing to invest in renewable water structures as they would prioritize water management as a ‘pressing issue’.

Desalinated unit costs

Following the in-depth analysis of desalination on the water supply system of the CCT, desalinated unit costs are a product of the capital and operational cost over time corresponding to the amount of megaliters produced. Capital cost (CAPEX) consists installment and material cost, while operational cost (OPEX) is derived from energy cost, employment cost, membrane cost and treatment costs. Additionally, an environmental impact is calculated as a function of cost.

Environmental impact

The environmental impact can be established by the fishery revenue gap. The more brine residue dispersed into the sea by means of the desalination plant, the more ‘unhealthy seawater’ (depending on the placement of the dispersion) – which in time will be detrimental for the fish population. Even though the shortened lifespan of fish is already an argument for some environmentalists, this research puts the fish population into a financial setting: the less fish than usual, the larger the fishery revenue gap since these fishermen in the area will have less of a pool of fish to gain profit from. Therefore, this lost revenue can be directly accredited to the desalination plant and is added to the operational costs of the desalinated capacity. The consideration of environmental impact translated into monetary units does not attempt to develop a full cost-benefit analysis and assessment of the total economic value of environmental resources. Neither it questions the conceptual and ethical implications behind economic valuation of the environment. It simply stands as a way for incorporating part of these direct economic impacts in the analysis.

Price elasticity through desalination

The corresponding price of the desalinated water is formed by the price Unit Reference Value by Blersch & Du Plessis (2014). The price correspondence is then compared to the normal price, and being put to the price elasticity of South Africa towards water. A calculation is made on the basis of the percentage the desalinated water is taking over time in the corresponding capacity – eventually flowing back to the domestic demand.

Additionally, following the CLD, a more extensive model has been created, capturing more of the dynamics in play. Firstly, the water supply and demand system of the CCT has been modeled extensively. Secondly, an in-depth analysis of the consequences of implementation of desalination has been performed through modeling and played out against the supply and demand system. The most critical reasoning for these modules are captured below; the total structures (Annex VI) as well as model reporting of every single variable (the model syntax) is to be found in Annex VII.

5.2 The water demand and supply system

In the SFD of the water supply system (timespan 2006-2056, timestep 1/12), the system represents four elements - dam water expansion, water supply through groundwater reserves, water supply through augmented re-use and water supply though desalination. The source the CCT is currently most reliant on, is dam water supply.

5.2.1 Dam water supply (non-augmentation)

Dam capacity is being measured by the amount of rainfall, which is a stochastic sequence. To capture this rainfall in a differential equation in multiple scenarios with multiple runs, the formula of rainfall (in line with the numbers and standard deviations of the CSAG (2017)) is:

Potential rainfall in catchment area:
*NORMAL(8000; (1000*assurance_of_supply); 4)*climate_change* (1)

Whereas 8000 - with a standard deviation of around 12% equivalent to 1000 - is equal to the amount of rainfall in the catchment areas (GreenCape, 2018a), climate change is now to be estimated to pair with a total of 10-15% decline in rainfall over the next 30 years (CSAG, 2017). Furthermore, this sequel is estimated to have a span of 4 years.

Around 9% of this rainfall actually flows in the dams ("rainfall precipitation in dams is 11 times as small as the amount of rainfall in the catchment areas" (GreenCape, 2018b)), to be seen in Figure 15. Dams can overflow when rainfall is overfilling their respective capacity, where the model represents this as a ratio. Should the dam capacity of 983 ML, which is current capacity, be reached, the stock would not fill up. In potential expansion plans it is known that only the Voelvlei Dam can be expanded, adding another 200 megaliters to the capacity. Upon completion, projected to be in 2026 (Du Plessis, 2018), the system adapts a maximum dam capacity of 1183 ML.

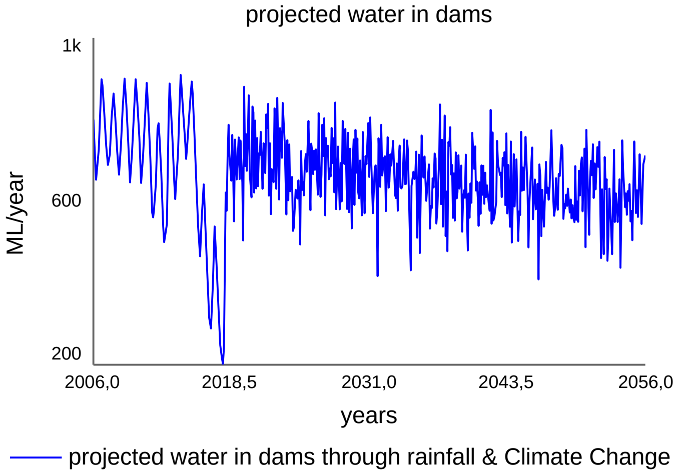


FIGURE 15: PROJECTION OF WATER IN DAMS THROUGH RAINFALL (CONTROLLING FOR 15% LOSS THROUGH CLIMATE CHANGE IN 2050)

5.2.2 Water demand

The ideal situation for the CCT is one where the water from dams is sufficient to the need of water – freshwater falling into the dams is, in fact, a 'free' water source. The total available water is a stock of water available minus the water supplied: basically, a 'fulfillment of the need'. Water demand is therefore a product of the economy and inhabitants of the CCT – built out of 70% urban demand, 15% mining and 15% industrial consumption. In the model, these elements are all generalized under a total domestic demand. Growth of total domestic water demand itself is, as reasoned before, modeled exogenously; only price effects and water restrictions affect the water demand. The model adapts the reference mode to start at the state where we are now, giving us the formula:

Water demand:
IF (TIME <2018)
THEN total_historic_demand
ELSE (domdemand(1+pricing_effect_by_desal))*water_restrictions_thresholds.* *(2)*

Where the thresholds are defined by the measurements the government had been taking now under the corresponding dam level conditions, and the pricing effect is a price elasticity should the price of water be higher (in this case due to desalination). In case the water demand exceeds the water supply at a certain point, the water supplied is not filled; one can see this as a 'backlog' where excess is noted. This is the water supply gap, with the corresponding formula:

Water supply gap:
MAX(0; water_demand-Total_Water_Supplied) *(3)*

In Figure 16, one can see the water demand over the water supply, solely by dam capacity – together with the water availability and the restrictions of the total dam capacity. Demand is excelling supply in as little as 2025-2027: therefore, augmentation is needed.

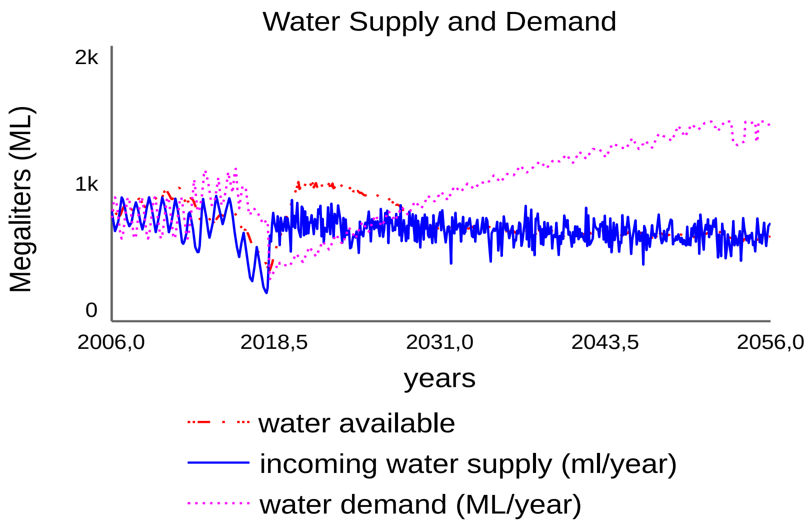


FIGURE 16: WATER DEMAND AND SUPPLY IN THE CCT (WITHOUT AUGMENTATION)

One way or another, water supply always has to correspond to the demand as this is a critical element for survival. A system failure can be considered once the supply is governed by the demand – the water supplied is equal to the water demand – resulting in a corresponding backlog, characterized as the water gap. The equation for water supplied is therefore:

Water supplied:
MIN(Water_Available ; water_demand) *(4)*

Augmentation can provide the solution to this system failure. The higher the population growth (Figure 17), the faster (and heavier) the water gap occurs, and subsequently the more the need for augmentation measures.

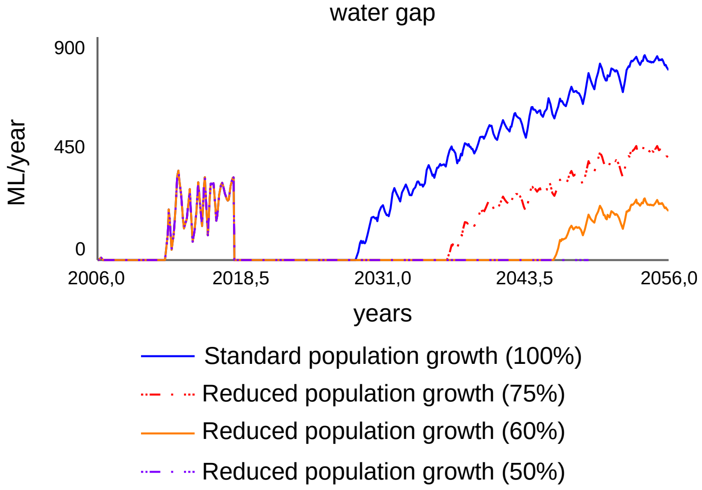


FIGURE 17: THE WATER 'BACKLOG' WITH DIFFERENT SCENARIOS OF POPULATION GROWTH. STANDARD POPULATION GROWTH (100%) = 1,2% PER YEAR (GREENCAPE, 2018), REDUCED POPULATION GROWTH (E.G. 60%) = 0,6* 1,2% PER YEAR

5.3 Augmentation

Since South Africa is a land with many problematic cases, the government needs to spread their priorities. It is hardly possible in the current state of the country with the limited budget available through either corruption or political instability in the country to reach a state of pro-active investment on water (Winter, 2018). Therefore, interconnections between the water gap and augmentation is created; the higher the water gap, the more the government is willing to invest in response to this apparent water gap. In the model, every individual method of augmentation can be taken into consideration by using a switch.

5.3.1 Groundwater extraction

The same rainfall that flows in the dam also flows to aquifer regeneration, although on a much lower percentage (4%, GreenCape (2018a)). In Cape Town, extraction of groundwater finds possibilities in two primary ways - unauthorized groundwater extraction from individual boreholes and through the use of groundwater extraction and treatment structures. The model is designed as a responsive model; if the water gap increases, augmentation will be larger since there is more money available from the government. In case the aquifer reaches a critically low level, water cannot be extracted from this source anymore.

5.3.1.1 The TMG aquifer

The TMG aquifer, where currently 10.000 ML of water is stored (Duah, 2010) replenishes with a regeneration delay of 20 years (Xi, 2013), whereas it would be depleted through human extraction. The extraction is defined by either borehole capacity or structural groundwater capacity increase. The aquifer is tightly bound to the groundwater capacity flow. In the model, the aquifer serves as a limiting factor – in certain capacity (below 4.000) the model hits a threshold; groundwater extraction will be restricted to smaller values than originally intended. The model represents that extracting too much groundwater could backfire on the government in the form of limited supply, in the rationale of over-extraction (De Clerq, 2018; Botha, 2018). With current parameter settings, where groundwater capacity is installed to be an extra 200 ML of supply, the aquifer level can be seen in Figure 18.

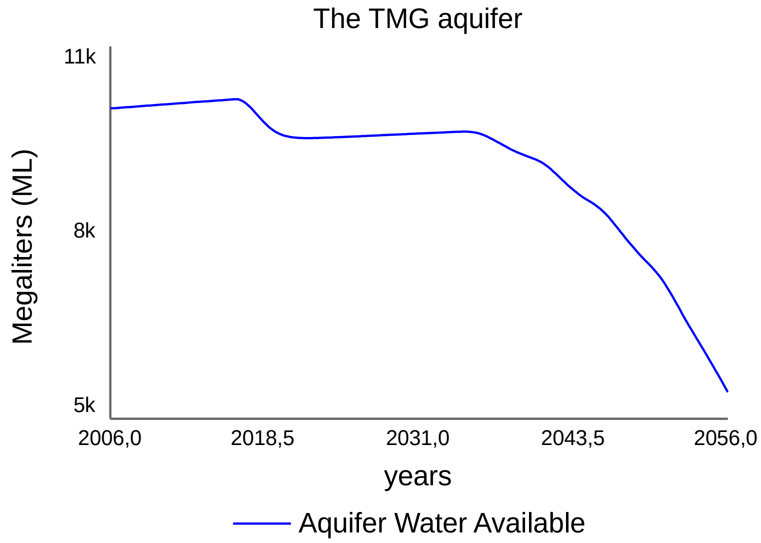


FIGURE 18: AQUIFER WATER AVAILABLE IN CURRENT AUGMENTATION PLANS

5.3.1.2 Borehole extraction

Borehole extraction is characterized as a function of the water supply gap. Boreholes are being created without authorization, whereas at one point the borehole capacity exceeds as much as 50 megaliters per year; the stock of borehole capacity increases, directly being an extraction factor for groundwater. Since boreholes are unauthorized it is not monitored how much water is being extracted. However, an educated guess estimates this amount to be around 25 megaliters (Figure 19).

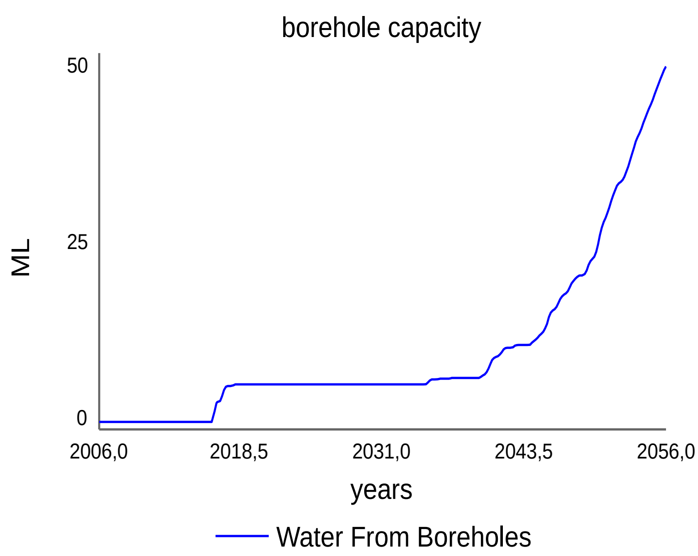


FIGURE 19: WATER AVAILABILITY FROM BOREHOLES

5.3.1.3 Groundwater extraction structures

Responsive to the water supply, a graphical function (Figure 20) has been created in line with current plans of the government, adjustable with a multiplier. Should the water supply gap be larger, the model would respond accordingly – whereas a more extreme gap would correspond with more rigorous measures. Since groundwater extraction is the cheapest, most accessible alternative to dam water supply, the measure can shoot up to a relatively high amount in augmentation.

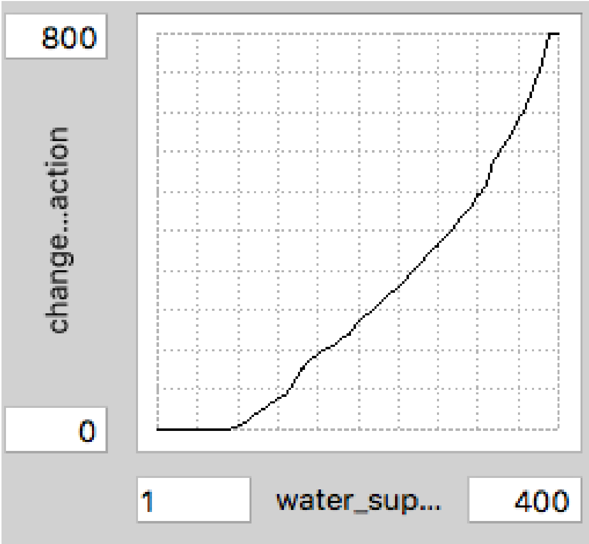


FIGURE 20: GROUNDWATER AUGMENTATION RESPONSIVE TO THE SUPPLY GAP

In the system, both groundwater extraction and aquifers corresponding to current proposed capacity and levels are being represented in Figure 21. One can see the amount of water being extracted now – whereas water extraction would activate around 2032 when the water gap is considered high. The installed capacity fulfills the water gap (whereas the line decreases) and then shoots up again since there is a growing population every year.

Additionally, a systemic overshoot and collapse is also captured when the aquifer gets depleted. In current course, this is not the case. Nevertheless, in case of over-extraction (Figure 22, multiplier set to 2) the system would respond with an instant drop in groundwater extraction – which is water that cannot be returned as the aquifer does not recover instantly. There is large uncertainty about the corresponding critical level of the aquifer (De Clerq, 2018; Kruger, 2018); the threshold levels are therefore to be considered illustrative until clarification on the subject is found.

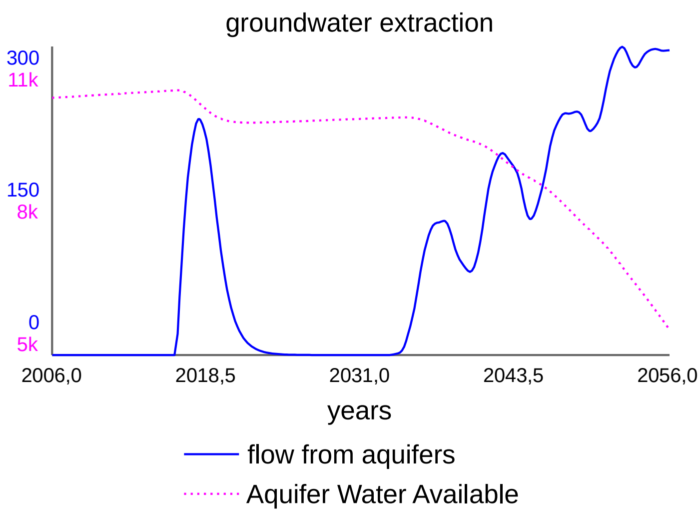


FIGURE 21: GROUNDWATER EXTRACTION IN CURRENT STRUCTURES

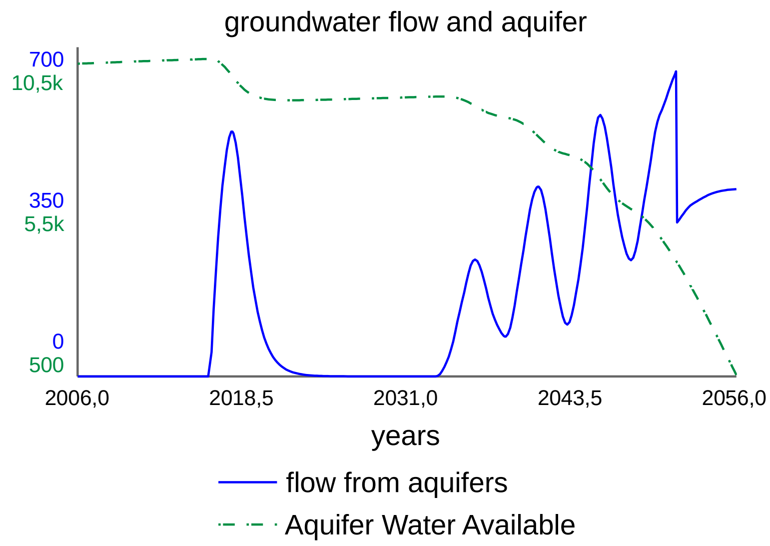


FIGURE 22: GROUNDWATER OVERSHOOT WITH MULTIPLIER *2

5.3.2 Water Re-use

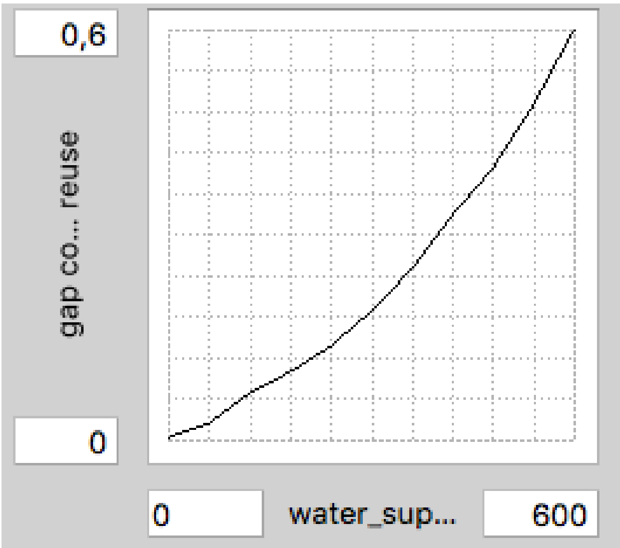


FIGURE 23: WATER RE-USE AUGMENTATION RESPONSIVE TO THE WATER GAP

Particularly on the industrial sector there is major ground to cover in water re-use. Nevertheless, it is relatively hard and expensive to install water re-use structures in the city; therefore, the government is recently aiming for around 10 to 15% in water re-use. The logic in structure of water re-use is equivalent to the one of groundwater augmentation, the only limiting factor is the potential water supply in this structure. After converting the water gap into possible water re-use (by means of Figure 23), the conversion would be implemented gradually. Therefore, a smooth function is introduced. The formula for the threshold of water re-use is the following:

Potential Water Reuse:

IF(switch_water_reuse =1) AND (TIME >2018)
THEN (SMTH3(gap_conversion_to_reuse; 2)) ELSE 0 (5)

After defining this threshold, water reuse needs to be multiplied with the potential water – which is redirected from the total water supply. Hence, the formula for the actual water re-use is the following:

Actual water reuse:
*potential_reusable_water*potential_water_reuse* (6)

Corresponding with the water gap and current policy, a graphical representation of the gradual increase of water reuse can be seen in Figure 24.

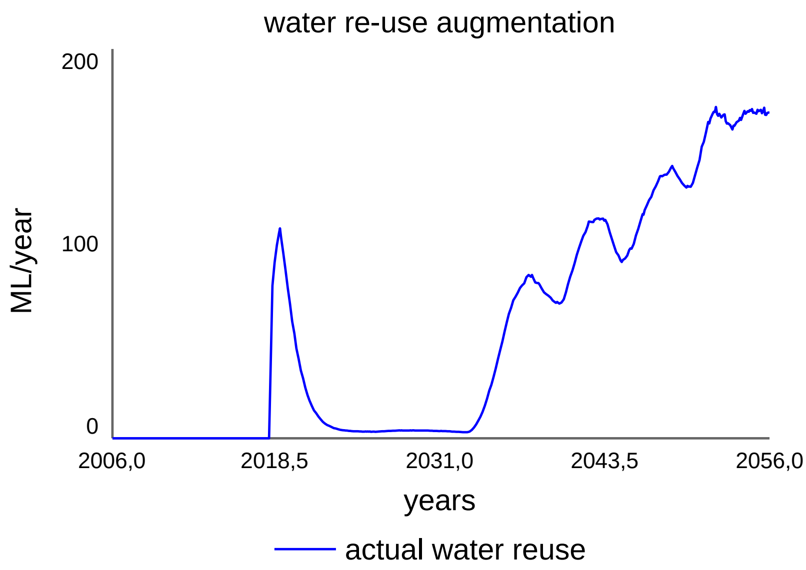


FIGURE 24: WATER RE-USE AUGMENTATION IN CURRENT AUGMENTATION PLANS (100 ML)

5.3.3. Desalination

The last focus point of the CCT is water augmentation through desalination. The model represents augmentation of 150 megaliters. It takes on average 4 years to install a desalination plant of such size (Arafat et al., 2017), which is taken into account in the model. The model accounts for a gradual increase of desalination (a function of desired and actual capacity over the adjustment time and a single implementation of desalination. Hence, the formula for desalination is the following:

Desalinated Capacity:
IF switch_desalination=1
AND (TIME >2018)
THEN (IF gradual_desal_increase_switch=1 THEN (desired_capacity- *(7)*
actual_capacity/capacity_adjustment_time)
ELSE single_desalination_implementation)
ELSE 0

The stock of desalinated capacity is captured controlling for the options 'with maintenance' and 'without maintenance' (Figure 25). With maintenance, desalinated capacity stays the same but is inferred with more cost, without maintenance it is merely a pulse with a plant depreciation of around 25 years (Arafat et al., 2017). In current augmentation plans, graph 5 shows desalinated capacity with and without plant depreciation.

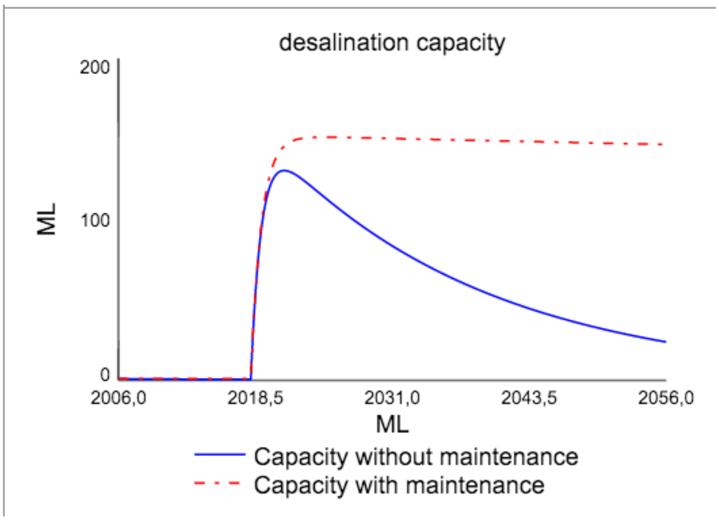


FIGURE 25: DESALINATED CAPACITY IN CURRENT AUGMENTATION PLANS

Desalinated capacity fills a part of the supply, resting an assurance of 100%. To see the entire picture of augmentation within the model and to see the augmentation matters in relation to each other, Figure 26 shows a composite graph. In Figure 27, one can see how augmentation would play out on the water supply and demand system in current plans; in the model, the augmentation plan is (predominantly in later years) on the edge of being insufficient.

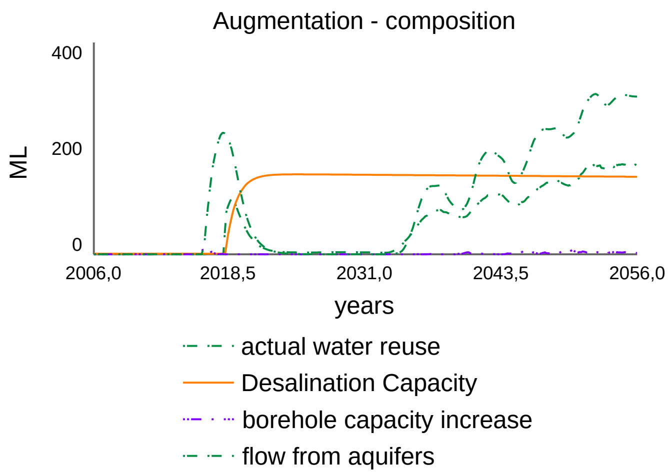


FIGURE 26: SYSTEMIC REPRESENTATION OF CURRENT AUGMENTATION PLANS OF THE CCT

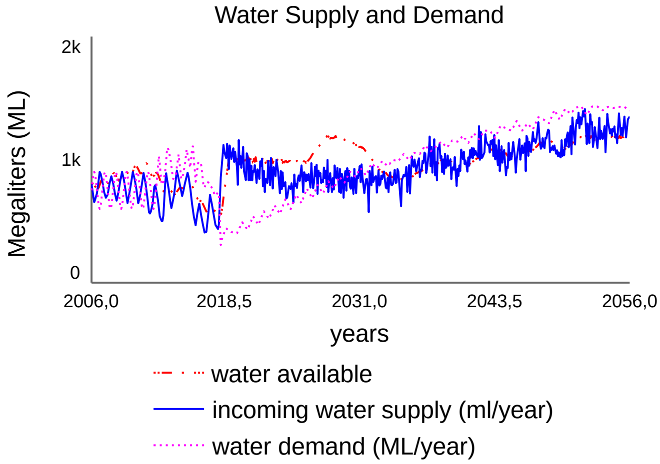


FIGURE 27: WATER SUPPLY AND DEMAND IN THE CCT (WITH AUGMENTATION)

5.4 In-depth Desalination

Arguably one of the most useful possibilities of System Dynamics is that the method can capture various levels of interconnections on different scales simultaneously. Scaling (or: working out an element of the model in detail, to see how this element works out on the total model) can be utilized to a far extent, whilst ensuring that the model calculates its interdependencies on the ’common denominators’; the units of the model. Although the possibilities are present to investigate every single form of augmentation as the ‘high level water demand and supply’ model has been created, this research chooses to focus on desalination in detail, and see how this would impact the high level model.

More detailed, conforming with the larger spectrum of the water supply and demand system of the CCT, this research tends to provide an in-depth research on the option of desalination, standardly set within current WC/WSM plans of 150ML/D (GreenCape, 2018b). The SFD for desalination is created following the CLD: the larger the water gap, the more the need for desalination. The more desalination, the more environmental cost, synergizing with the total cost of the production of desalinated water. The more costs, the higher the water price – balancing the water demand through price elasticity. Therefore, the following subchapters cover these subsequent sectors. Firstly, the environmental cost of desalination is analyzed in detail, followed by the total desalination cost, whereas the final subchapter ‘closes the loop’ with related price effects on demand.

5.5 Desalination – Environmental Cost

To add an environmental cost to the operations of desalination, one needs to calculate its negative impact on marine biology and convert this into a financial setting. In the model, the environmental impact module functions in essentially the same way as an Environmental Impact Assessment or EIA (in line with multiple elements of the EIA's of Volwaterbaai and the port of Saldanha Bay (SRK Consulting, 2007; 2014)): to calculate the associated impact through the amount of brine dispersion in the proposed installed capacity of desalination, as a negative effect of income of the fisheries of pelagic fish species, plus additional costs to eradicate the toxic waste of the desalinated capacity. Prior to the explanation of the module, remarks on the approach are to be made for model boundary purposes.

Firstly, the model takes only the pelagic fish population into account, as pelagic fish is the most abundant fish species in the Western Cape. To map the entire marine biology of the Western Cape would become fairly complex and strive past the goal of this model, whereas this would also complicate matters in terms of coupling this to a financial accreditation to the desalination plant.

A second remark should be made on the associated fisheries: a wide margin has been taken as approximation – in the Western Cape, most of the fishery firms are informal ones. Therefore it has been difficult to track the actual number of fisheries, this is a rather static constant approximation in the module.

A third remark on the module is one of accreditation. In terms of accreditation, it is a fundamental question who is going to pay for the apparent loss of profit – especially on such a complicated matter as brine dispersion. When brine disperses, it will likely reside on a far location from the CCT due to currents, and it is likely not a singular cause-effect relationship to the premature death of fish; to directly accredit the loss of fish revenue to the desalination plant might be rather short-sighted. This clashes with an one of the founding premises of System Dynamics; to capture as much of the system as possible in a most representable way (Forrester, 1970). Although the capturing of the system can happen as accurately as possible, it then becomes a matter of jurisdiction rather than a direct certainty within the model. Nevertheless, the module claims a direct impact to be a direct, singular accreditation on the desalination plant. Should environmental issues be disregarded through jurisdiction the entire module of environmental impact does not hold ground, which would have significant effects on the desalination model.

5.5.1. Brine dispersion

Brine dispersion through desalination is, up until current states of technology, inevitable.

Around 60% of water in the desalination process is leftover as brine, which means that for 1 megaliter of desalinated water one has around 2,5 megaliters of water in the process, whereas 1,5 megaliters is leftover as brine. The stock of brine discharge is therefore consisting of potential water intake in the desalination process towards the actual water being desalinated. Additionally, over time, there will likely be a factor of innovation pushing back the brine dispersion. This parameter could be adjusted as it is a fairly uncertain factor. Incoming brine discharge is formulated as follows, with the corresponding graphs to be found in Figures 28 and 29.

Brine disposal:
*(potential_water_in_process*actual_brine_dispersement) *innovation.* *(8)*

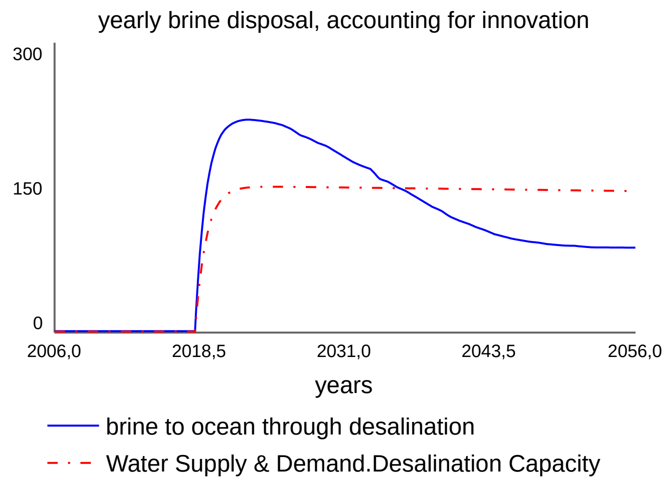


FIGURE 28: YEARLY BRINE DISPOSAL IN DESALINATION CAPACITY OF 150 ML

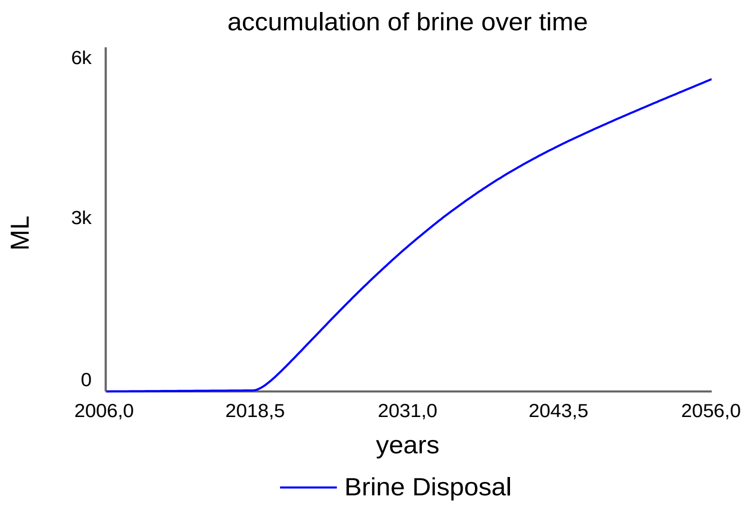


FIGURE 29: ACCUMULATED BRINE DISPOSAL FOR A DESALINATION CAPACITY OF 150 ML

5.5.1.1. Brine dispersion to currents

The model attempts to capture brine capacity in the two main currents - the Benguela current (south of the CCT) and the Aguillas current (west of the CCT). Characteristic of the Benguela current is that it is full of fish. The Aguillas current has a smaller population of fish. Together with these demographics the Benguela current is characterized as a coastal habitat. This is a warm water stream where many groups of fish are situated. The Aguillas current however, is one with coastal up-welling (Lombard, 2018). Following Figure 30, knowledge of the CFD of Robinson et al. (2015) and the reassurance of a marine biology expert, the dispersion rates have been set on respectively .75 and .88 (Lombard, 2018).

Rating	Marine Habitats
1	High-energy oceanic coasts, rocky or sandy, with coastal-parallel currents
2	Exposed rocky coasts
3	Mature shoreline (sediment mobility)
4	Coastal up-welling
5	High-energy soft tidal coast
6	Estuaries and estuary-similar
7	Low energy sand-, mud- and beach rocks-flats
8	Coastal sabkhas
9	Fjords
10	Shallow low-energy bay and semi-enclosed lagoon
11	Algal (cyanobacterial) mats
12	Seaweed bay and shallows
13	Coral reefs

FIGURE 30: LEVEL OF DISPERSION MIXING (SADWHANI ET AL., 2005)

5.5.1.2 Pelagic fish through GIS mapping

For demographics on fish species in both the oceans, in Figure 31 a freely available GIS-map of the pelagic fish is created – where layer 1 is benthic and coastal habitats (blue, the small blocks on the northern gulf stream), layer 2 is the Table Mountain protection area (purple) and layer 3 is pelagic fish (blue, spans over the whole bay). Following the GIS and its current numbers, the population of the pelagic fish is created.

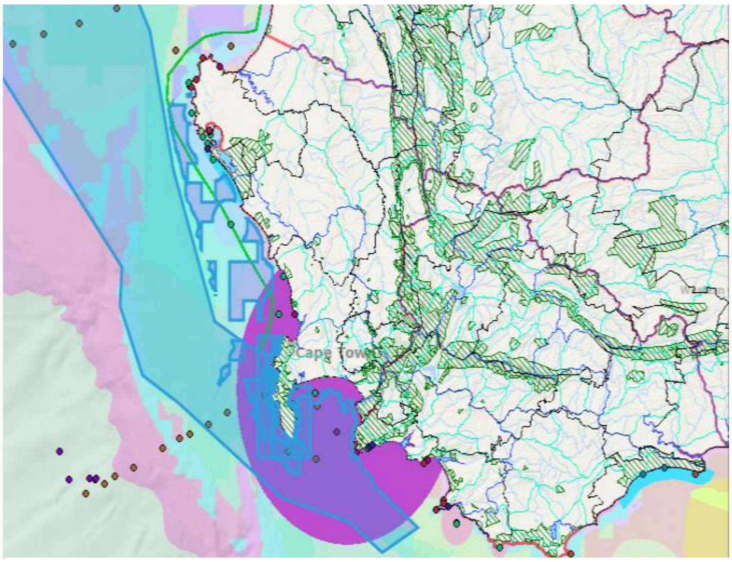


FIGURE 31: GIS MAP OF THE COASTAL HABITATS OF PELAGIC FISH SPECIES AROUND THE CCT (EGIS.GOV, 2018).

5.5.1.3 Fishery revenue gap

After calculating the pelagic fish in normal conditions (sub-module: 'normal fish') for both the Benguela and Aguillas current, the effect of brine is calculated on the lifespan of the fish. The module calculates the salinity in the residing area controlling for the Benguela and the Aguillas current, and the effect of the lifespan of the fish in line with the research of the Pacific Institute (2013), portraying the brine residue as a 'significant impact' on the marine environment. The more salty the water in the current, the heavier the effect; giving a decline in the fish species. These actual fish stocks are then being compared to the normal fish stock, calculated towards the normalized price of the fish. The fish stock in comparison for both the Aguillas and Benguela can be found in Figures 32 and 33.

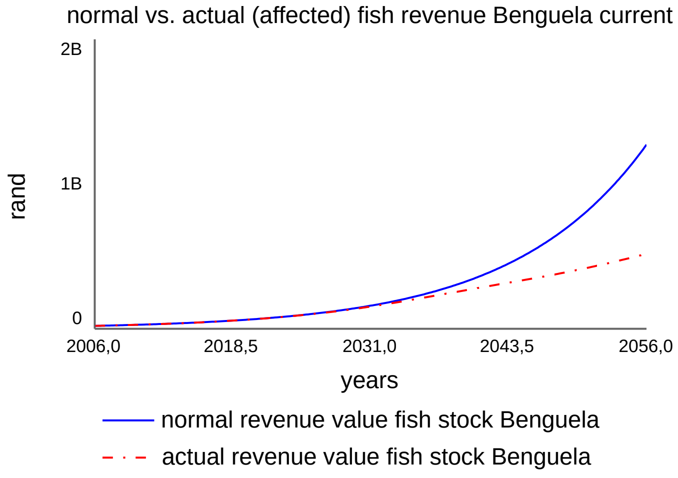


FIGURE 32: NORMAL AND AFFECTED FISH STOCK, CONTROLLED FOR THE BENGUELA CURRENT

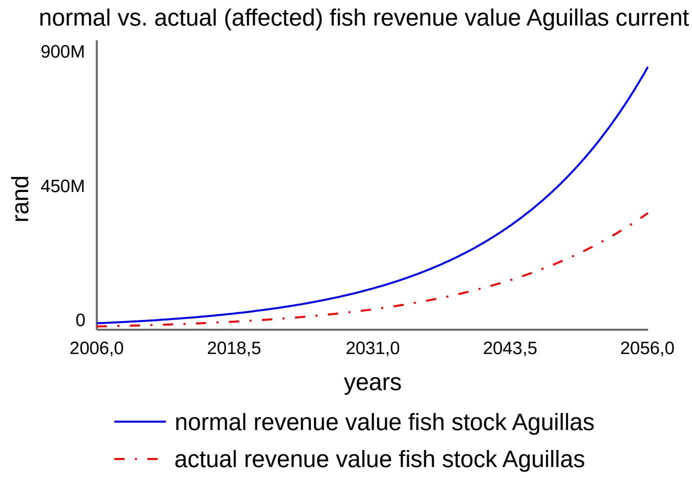


FIGURE 33: NORMAL AND AFFECTED FISH STOCK, CONTROLLED FOR THE BENGUELA CURRENT

Since the model is controlling for either the Benguela or the Aguillas current, the fishery gap would only imply on one of the two currents. The formula for the fishery gap produced is the following:

Fishery gap:
(normal_revenue_value_fish_stock_Benguela-actual_revenue_value_fish_stock_Benguela)
+ *(9)*
(normal_revenue_value_fish_stock_Aguillas-actual_revenue_value_fish_stock_Aguillas)

5.5.1.4 Total environmental cost

The second component for the cost of environment is the amount of toxic water being produced by membranes. Although relatively small (0.1% of water in the desalination process has become toxic (Arafat et al., 2017)), this stock of toxic waste has to be stored which infers a cost. The compounded environmental cost, a combination of the fishery revenue gap and toxic waste, is being represented in Figures 34 and 35 for placement of the desalination plant in either the Benguela or the Aguillas current respectively.

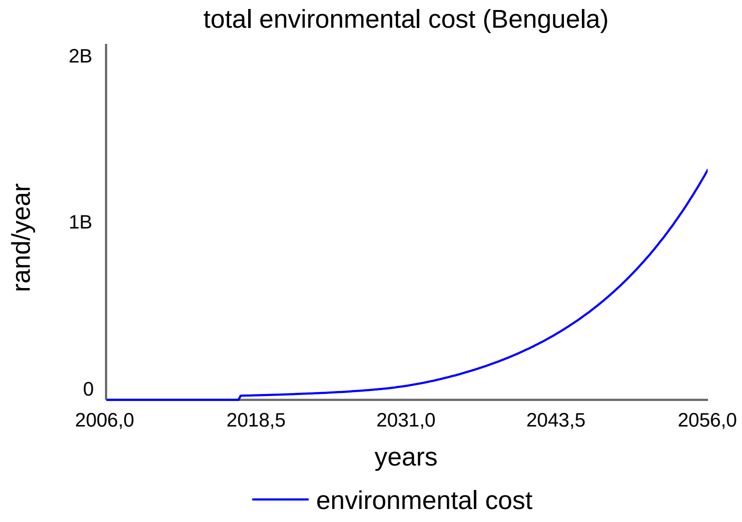


FIGURE 34: TOTAL ENVIRONMENTAL COST, CONTROLLED FOR PLACEMENT OF DESALINATION PLANT IN BENGUELA CURRENT

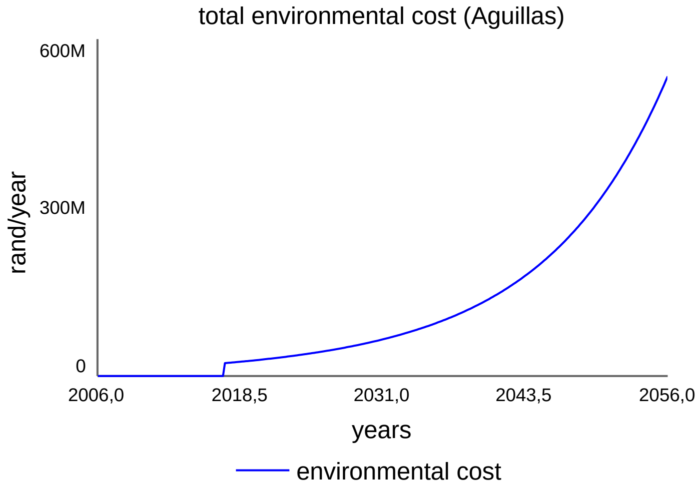


FIGURE 35: TOTAL ENVIRONMENTAL COST, CONTROLLED FOR PLACEMENT OF DESALINATION PLANT IN AGUILLAS CURRENT

5.6 Desalination – Total Cost

The cost for a desalination plant over time is crucial for the analysis of adjusted water price. Costs break down twofold: firstly, in an initial capital investment (CAPEX) corresponding to the desalinated capacity, and secondly in operational costs over time (OPEX) to keep the desalinated capacity running.

5.6.1 OPEX

The total desalinated cost of a RO-based plant is typically a function of mainly electricity cost (44%), labor costs (12%), membrane and chemical costs (21%) , environmental costs (solid waste) (4%) and other, fixed and maintenance costs (19%) (Figure 36).

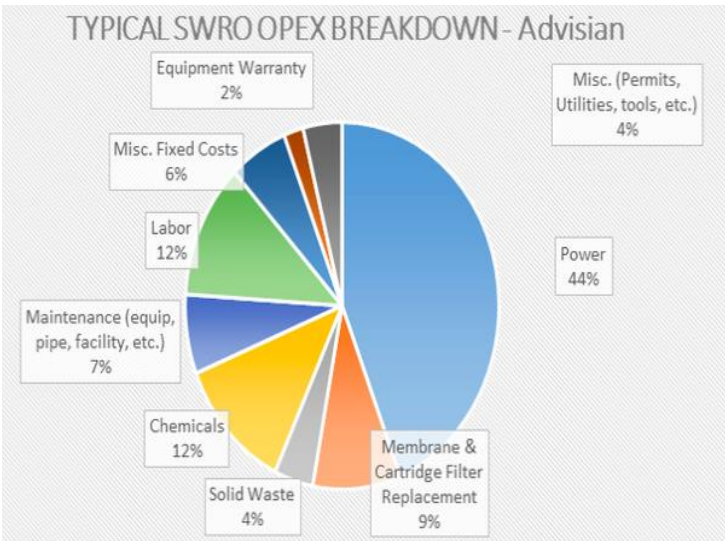


FIGURE 36: OPEX OF AN RO-BASED DESALINATION PLANT (ARROYO ET AL., 2012)

Operational costs (OPEX) can be functionally defined as:

OPEX:
f(energy, labor, chemicals, environment, maintenance) *(10)*

In a more detailed breakdown described below, the research adapts these numbers and explores the developments over time.

5.6.1.1. Energy costs

In the costs module, an in-depth submodule for energy costs has been created. In the desalination process, the method of Du Plessis et al. (2006) is adapted to define the technicalities of energy costing. Although a relatively old method, the results of this method are claimed by the author to still be on par. Although the guide by Du Plessis et al. (2006) tends to capture the whole costing process of desalination, this research has chosen only to include the energy costing functions of the method. The reasoning behind this is the static nature of the formulas: the costing functions are not accounting for external developments over time, whereas this system analysis has the focus to eliminate as much uncertainty as possible. Energy development in desalination is, although a downward trend in cost, subject to major variance (Figure 37). To endogenize every element of the energy cost in desalination would eliminate this variance as much as possible. A less time-related argument to capture energy in detail is one of being multifaceted. Where all other costs are rather singular (for example, there is only 'one' average in employment costs, or membranes are a singular process of 'buying materials and introducing these in the process') energy is multifaceted: energy cost accounts for demographics of the CCT, different costs through feed flows, increases in cost through temperature, energy costs in pre- and posttreatment processes, and so on. Therefore, the module attempts to capture the energy costing as detailed as possible.

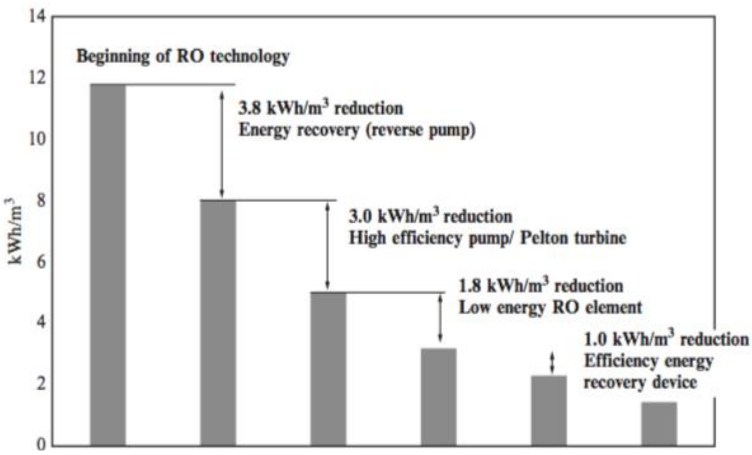


FIGURE 37: UNCERTAINTY ON ENERGY DEVELOPMENT (ARAFAT ET AL., 2017)

The sub-module of total energy costing breaks down in the energy costs of water pumping, the energy costs of pre-treatment and the treatment cost per Celsius. The first-order capital costs are being calculated through the steps introduced by Du Plessis (2006; 2018), as follows:

1. Determine the potential water in the process.
2. Identify the available saline water recovery and required pumping cost.
3. Determine the pre-treatment and post-treatment requirements.
4. Determine the plant energy consumption.

1. Determine potential water in process.

The process of determining the potential water is one of plant capacity multiplied by 2.5, as this is the percentage of water coming in untreated. Furthermore, it is relevant to calculate the operation capacity of the plant – which is being calculated by hourly production rate to determine the daily capacity of the plant. Typically, this value is set in regard to the fraction of the day for which this desalination plant is operating at full capacity, which is around 90-95% of the day (Du Plessis, 2006). The formula for hourly production is therefore:

*potential_water_in_process/24*fraction_of_day_plant_at_full_cap* (11)

2: Identify the available saline water recovery.

The converted water to the desalinated product after passing through the membrane is called water recovery; the remainder is discharged in the form of concentrated brine. Here, the norm of .40 is maintained. To calculate the energy cost for pumping, an hourly feed flow has to be multiplied with the hourly production rate: this feed flow is a flux consisting of two passes. Together, costs of these both pressures (although depending on more factors), presented as pumping cost, is on average around 15% of all energy cost, accounting to a per ML cost of around 100.000 Rand. The formula for this pumping cost is therefore:

Pumping cost:
*water_recovery_factor*energy_pumping_cost_per_ml* (12)

3. Determine the pre-treatment and post-treatment requirements.

Pre-treatment and post-treatment requirements are typically around 30% of the total energy cost (Arafat et al., 2017). The methodology of Du Plessis et al. (2006) suggests to add pre- and posttreatment costs to feedwater pressure; however, this flow rate is subject to much variance where this model tends to eliminate variance and adapts averages. The average of pre-and posttreatment cost is therefore taken, concluding to around 200.000 Rand per ML. The subsequent formula is therefore:

Pre-and posttreatment energy cost:
*potential_water_in_process_1*energycost_per_ML* (13)

4: Determine the plant energy consumption per Celsius.

Subsequent to step 3, energy consumption per Celsius in the context is fairly static in its traditional way. The concept of calculus per Celsius is relevant, however, the formula would infer major variance. Therefore, the model takes the remainder of the energy costing into account which is then composed per ML and temperature change rather than water feed per Celsius. Temperature development is created as an adjustable graphical function, spanning to an extra 20% in water temperature over the time horizon. Therefore, the formula for energy cost per Celsius is the following:

*Energy cost per Celsius: (potential_water_in_process_1*cost_per_celsius_per_ml) *projected_temperature_increase_per_ml* *(14)*

5.6.1.2 Total energy cost

After composing all elements of energy cost through desalinated together, an innovation factor in line with Arafat et al. (2017) is introduced. The total energy cost is shown in Figure 38.

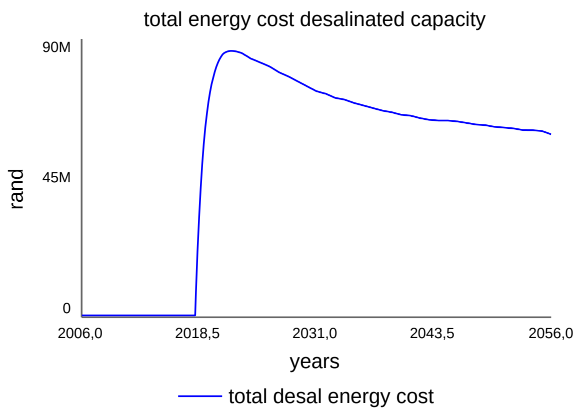


FIGURE 38: TOTAL ENERGY COST FOR A DESALINATED CAPACITY OF 150 ML

5.6.1.3 Labor costs

The costs for labor are being calculated on the number of employees that are needed for the production of 1 megaliter (typically around 2 employees (Arafat et al., 2017)) and the inferred cost for these employees. This has been estimated by the average yearly salary of an experienced engineering factory worker; a salary which is around 140.000 Rand per year (Statssa, 2017). Over the years, it is suggested that automated processes will likely take over the manual operations for a fairly large part; a graphical function in the model therefore suggests that around 70% of production is going to be automated by 2056 (Figure 39). The subsequent formula is the following:

Labor cost:
Desalination_Capacity(avg_salary_employment*employees_per_ML)* *(15)*

5.6.1.4 Maintenance and various costs

To calculate the maintenance costs over time, a proxy has to be made on the development over time. Subsequently, in conversation with an expert stakeholder (Du Plessis, 2018) and in connection to the literature (Arroyo & Shirazi, 2012) the maintenance costs have been set to around 120.000 Rand per produced megaliter with an innovation factor of around 40% up until 2056, which is taken into account in the costing function per megaliter. Maintenance and various costs therefore holds the formula:

Maintenance and various costs:
*Desalination_Capacity*maintenance_&_various_costs_per_ML* *(16)*

The corresponding graph for the maintenance and various costs can be found in Figure 39.

5.6.1.5 Membranes and chemical costs

In the same way as maintenance and various costs, membrane and chemical costs have been calculated. Data on the amount and cost of membranes per Megaliter was available through Arroyo et al. (2012), making up for a membrane cost of around 100.000 rand per megaliter (Figure 39). It is assumed that membranes, since these are set chemical particles, are likely only subject to the market instead of to innovation – therefore, an estimate of 20% reduction in cost due to competition until 2056 has been assumed. The subsequent formula for membranes and chemical costs is:

Membranes and chemical costs:
*Desalination_Capacity*membranes_&_chemicals_costs_per_ML* *(17)*

5.6.1.6 Total cost: f(*energy, labor, chemicals, maintenance, environment*)

The outcomes of the total cost seem to be in line with Figure X, where the division of the operational cost is made. A discrepancy is found in environmental cost over time (particularly in the period of 2040-2056), and is therefore not being taken into account in Figure 39 which is a representation of the energy, labor, chemicals and maintenance cost.

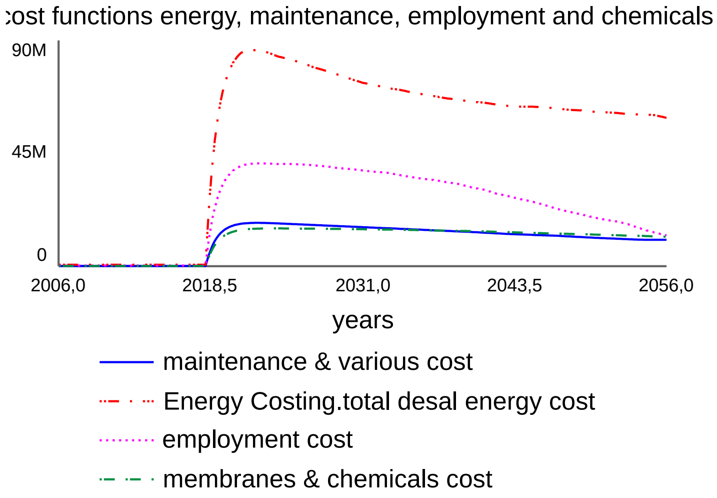


FIGURE 39: *F(*ENERGY, LABOR, MAINTENANCE, CHEMICALS) CONTROLLING FOR 150 ML DESALINATED CAPACITY.

Over time, the environmental cost is not to be ignored: at a certain point, the reinforcing environmental cost governs and almost dictates the total operational cost. In an accumulation, the total OPEX controlling for both the Aguillas and Benguela current is represented in Figure 40:

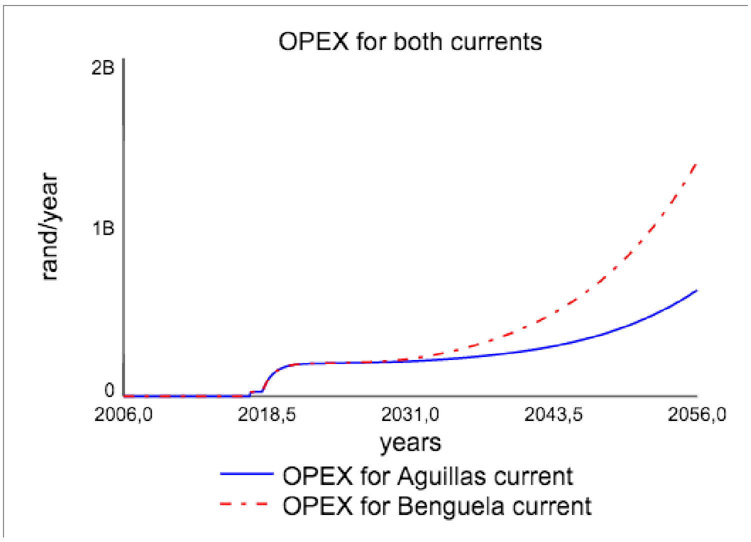


FIGURE 40: OPEX CONTROLLING FOR BOTH AGUILLAS AND BENGUELA CURRENT WITH A DESALINATED CAPACITY OF 150 ML

5.6.2 CAPEX

The capital cost or initial investment is to be calculated through mainly two parts: the expenses of the installment to get fully operational and the expenses on required material. Additionally, the more volume of material and capacity of the plant, the more reduction though bulk discount; also, through the years a likely innovation factor has to be taken into account. Since the procedure of installing a plant is a one-time procedure, a PULSE function has been introduced on both material and installment costs. Total plant installment costs have been estimated to be around 2 billion rand. To endogenize this in the system, the model adapts a price per megaliter which is rather a slight instance higher than the actual cost. Volume efficiency corrects this behavior on both plant installment cost and material cost. Innovation efficiency however controls the reduction in material and plant cost over time as this is likely to decrease. Due to these structures, the model adjusts itself according to placement costs for a certain capacity for a certain time period. In Figure 41, one can see OPEX and CAPEX over time (controlling for the Aguillas current), should the proposed desalination plant be installed in the year of 2019. Subsequently, Figure 42 shows the accumulated cost of the desalination plant over time.

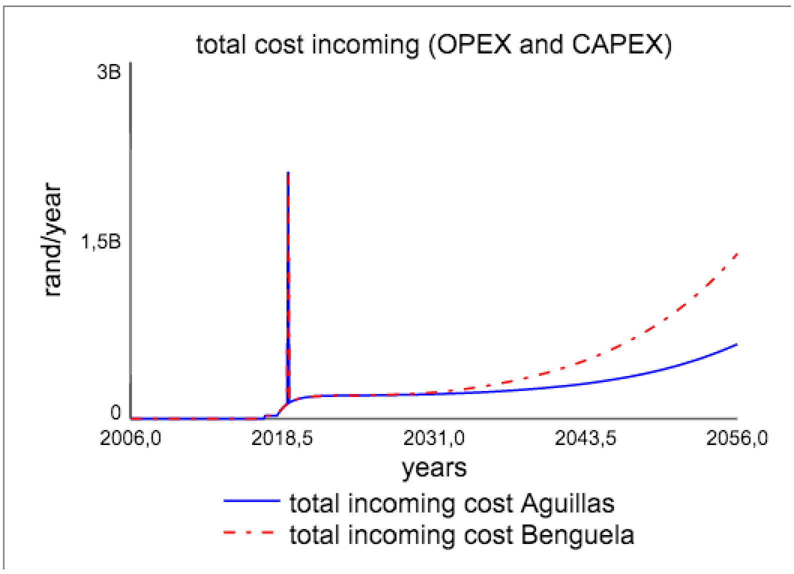


FIGURE 41: TOTAL INCOMING COST FOR BOTH CURRENTS, INSTALLMENT IN 2019 WITH DESALINATED CAPACITY OF 150 ML

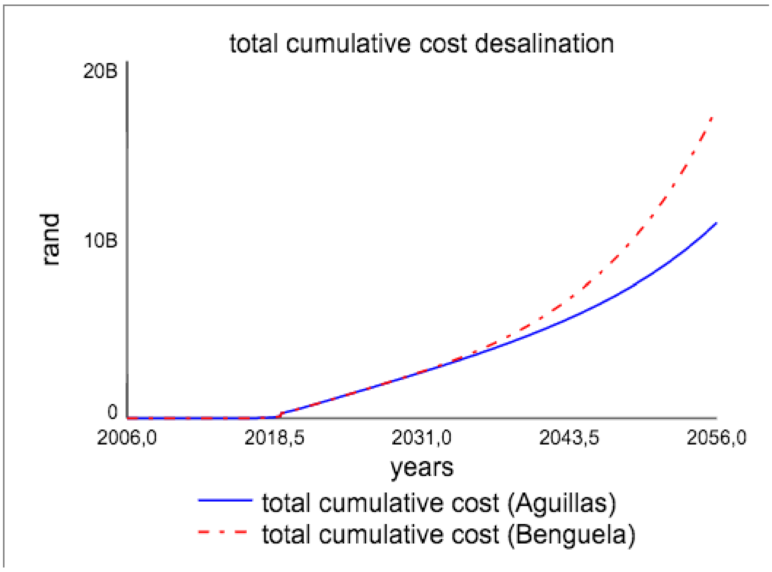


FIGURE 42: CUMULATIVE COST DESALINATION FOR BOTH CURRENTS, INSTALLMENT 2019 WITH DESALINATED CAPACITY OF 150 ML

5.7 Desalination – Price Effects

As the literature showed (GreenCape, 2018b), desalination was thought to be the most expensive method of augmentation with a water price of as much as 15 rand per produced kiloliter. The model complies with these premises; it is in line with current findings. The question on the socio-economic impact due to the price effect of augmentation measures (here: desalination) remains; the model tends to cover this by estimating the price elasticity on three different income groups: low, middle and high-income groups.

5.7.1. Desalinated water price vs. normal water price

The model takes the total cost flow of desalinated water into account (OPEX and CAPEX), for the reason that this would play out to be a continuous burden for the government instead of an accumulating one. This price is then set to the corresponding URV, in line with the method to calculate an URV of Du Plessis et al. (2005) – showing an average desalinated cost of 15 rand per KL, which is in line with the findings of the Water Outlook Report (GreenCape, 2018b). The desalinated URV price is then being compared to the normal water price of surface water (around 5 rand per KL (GreenCape, 2018b)) to estimate the relative increase in price. The subsequent formula for the normalized price of desalination is therefore as follows:

Normalized price desalination:
URV_desal/Normal_cost_Damwater *(18)*

5.7.2. Price elasticity to income group

After calculating the normalized price of desalination, this added price is subject to elasticity on water. In the book 'The economics of Water' by W. Meyer (2012) an in-depth analysis has been made on the economics of water in South Africa. Through intensive research the book maintains the values designed by Veck & Bill (2000) for price elasticity on water in South Africa. Although relatively inelastic, the values that are found are presented in Table 5.

TABLE 5: PRICE ELASTICITY (PE) OF WATER IN SOUTH AFRICA (VECK & BILL, 2000). PERCENTAGES INCOME LEVELS IN THE CCT: STATSSA, 2018

Group %	PE Indoor Use	PE Outdoor	PE Total
Upper income 5%	-0.14	-0.47	**-0.19**
Middle income 27%	-0.12	-0.46	**-0.17**
Low income 68%	-0.14	-0.19	**-0.14**

In the CCT, a division of income has recently been analyzed by the Central Bureau of Statistics in South Africa (2018), as to be seen in Table 5 as well. The normalized price of desalinated water is firstly multiplied by its total elasticity per income group, followed by a multiplication of the percentage that that respective income group covers. Afterwards, these values are being accumulated and divided by 3 to create a normal average. The subsequent graph of every individual price elasticity is to be found in Figure 43, together with the total elasticity. One can see the fishery gap governing the latter part of the graph, making up for a stronger price elasticity though a larger costing.

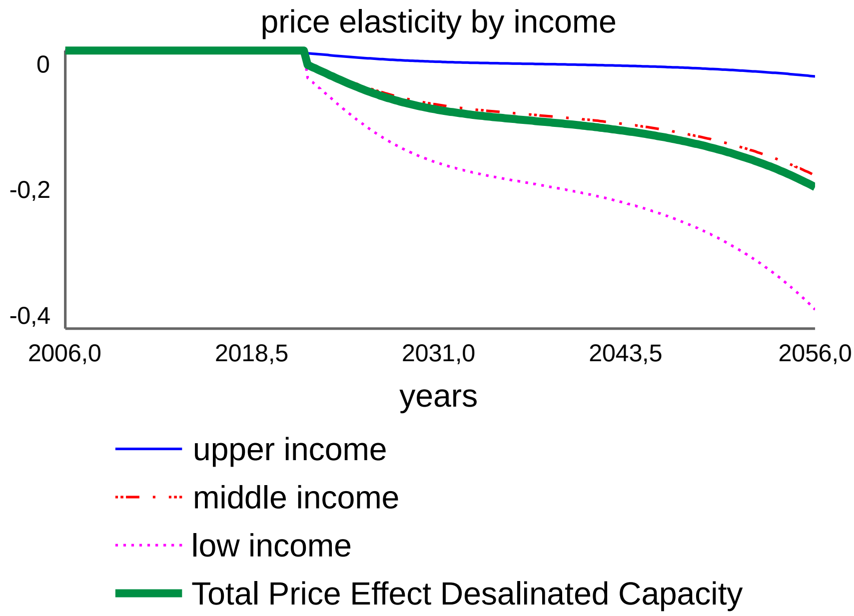


FIGURE 43: PRICE ELASTICITY THROUGH DESALINATED CAPACITY OF 150 ML

5.8 Price Elasticity to Demand

The increase in water price corresponds with a balancing factor in demand – the more expensive water becomes, the less that people are going to buy water. Water is essentially a product of the market, although relatively inelastic.

5.8.1. Price elasticity on demand due to desalination

First, the percentage the desalination makes up from the entire water supply system needs to be calculated as the price effect can only impact on its percentage of the whole water spectrum (Figure 44) - which is governed by surface water as well as all possible forms of augmentation in the WCWSS plan. This percentage is relatively straightforward, expressed as:

Percentage covered by desalination:
Desalination_Capacity/Water_Available *(19)*

Once the total desalinated capacity is calculated, the 'real' price effect can be calculated by multiplying the number of percentage that is covered by desalination with its total price elasticity (Figure 45). The more expensive the desalinated water becomes (mostly due to the environmental instruments), the larger the pricing effect is as the percentage that is covered by desalination stays relatively the same (around 15%). Basic calculus would give 15% of difference of 10 Rand = +1,5 Rand for the added price, amounting to a total water price of R 6.25 per kiloliter. This change of 1.25 Rand per kiloliter has a direct effect on the water demand: the more expensive water becomes, the lower the demand – which can be seen as a desirable situation for the collective, but rather undesirable for the individual.

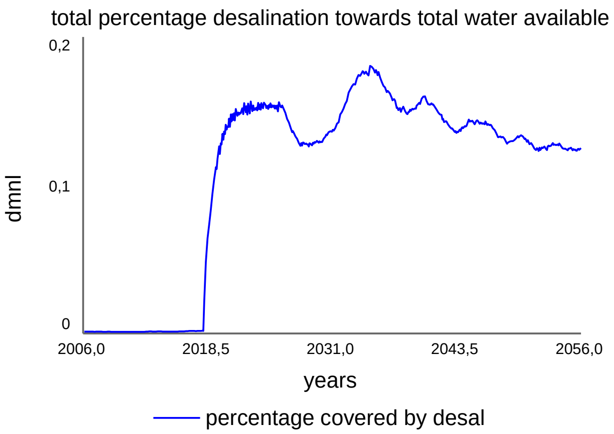


FIGURE 44: TOTAL PERCENTAGE IN TOTAL WATER AVAILABLE THAT IS COVERED BY DESALINATION (150ML)

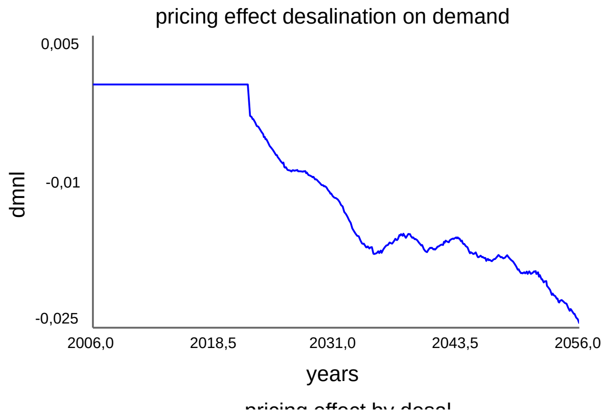


FIGURE 45: SUBSEQUENT EFFECT OF PRICE ON THE DEMAND (150 ML DESALINATION)

5.8.2. Water demand effects

As water demand effects are calculated, the government has multiple opportunities to cover for the water tariff to improve the socio-economic situation of the city. However, this is a trade-off for the government as water demand would rise through this cover; water keeps its same price, whereas the demand function would roughly stay the same although the government has to pay as the water price per produced kiloliter needs to be accounted for. In Figure 46, multiple scenarios on demand are simulated.

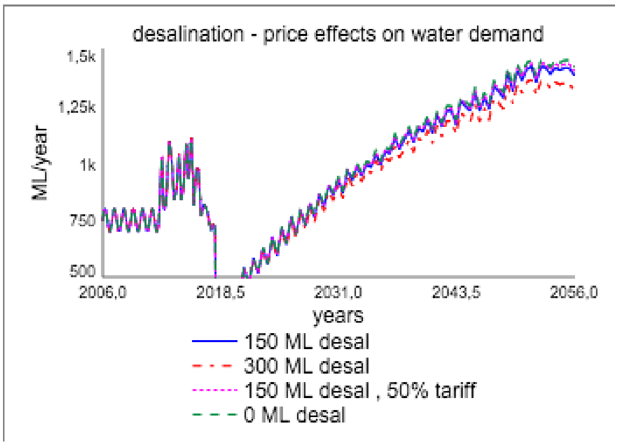


FIGURE 46: PRICE EFFECTS ON DEMAND, CONTROLLED FOR MULTIPLE OPTIONS OF DESALINATION

5.9 Desalination - effect on water availability

Within the context of the entire water system of the CCT, desalination can provide a freshwater supply source with essentially 100% assurance of supply. The model explores the reassurance of solely desalination in current augmentation plans on the entire water supply gap, the 'backlog' of water, in Figure 47.

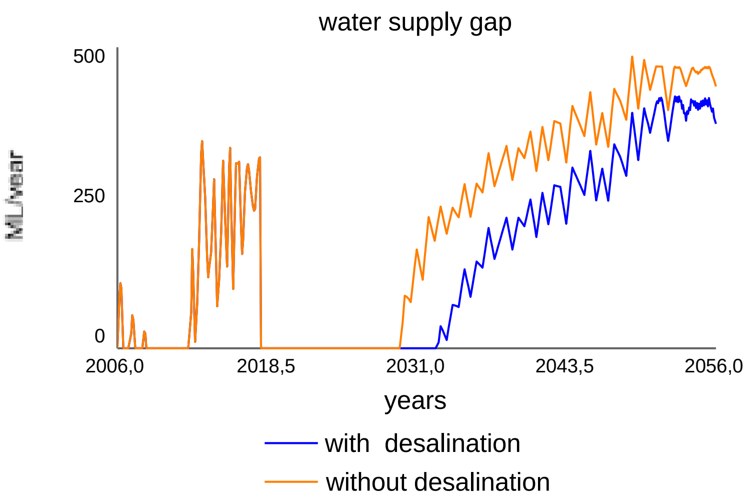


FIGURE 47: WATER SUPPLY GAP, CONTROLLED FOR THE INTRODUCTION OF DESALINATED CAPACITY (150ML)

Resulting from Figure 47 it can be concluded that, by implementing only 150 megaliters of desalination, the system reacts accordingly; through both the supply of extra water and reduced demand through higher pricing elasticity, demand can be covered a few extra years before water need takes over. Nevertheless, this graph is solely showing the introduction of desalination on the water supply and demand system; by implementing various methods within the supply mix, this gap can be mitigated and likely avoided.

6. Discussion

This chapter tends to provide insight on both content of the model and outcomes of the process; a model is only as useful as the (in)direct impacts it provides. First, the overall scenario-setting of the model is discussed, followed by a linkage to literature and explanations of the boundary settings. In the last subchapter the apparent usefulness of the process is described. As ACTDesal functions as a springboard to explore the applications and usefulness of System Dynamics on such a complex problem as water management in the CCT (the spectrum of Assessment of Cape Town Water, ACTWater), the research is to be taken as a work in progress. Possible ways forward are therefore proposed in the concluding subchapter of the discussion section.

6.1 Overall discussion on simulation results

In the situation of Cape Town, the problematic situation was one of water instability. As has been reported multiple times in the research, dams are reaching their limit capacity, hence the government needs to find alternative solutions to support a rapidly growing population through urbanization for the long term. The model tends to seek answer to this problem to endogenize the water system as a whole and see how multiple options (decision-points for the government on water augmentation) play out in the realm of the CCT water system. Amongst multiple other possible decision-points following from the model, an overview of the most relevant decision points (that is, in the choice of implementation of desalination) will be provided in this section – showing the relevance of the model. The model remains exploratory, which implies that no hard recommendations are expected in regard to the decision points.

<u>Decision point 1: Augmentation – Demand and supply</u>

Firstly, augmentation interventions as they have been imposed by the government in the CTWRP were analyzed by the model. These interventions have been put against three scenarios: standard population growth (100%), smaller population growth (75%) and poor population growth to be found in the Annex for scenario-setting, Annex IX, Figures 1A – 1F. The outflowing water gap is to be shown in the same graph. Subsequently, one can witness the augmentation matters to be a 'waste of money' with poor population growth (Annex IX, Figure 1C), whilst being an absolute necessity in case of full population growth (Annex IX, Figure 1D).

Simultaneously, on the supply side, climate change is a factor of uncertainty for the CCT. The development over time is unknown for everyone. The study adopts the approach that the higher the climate change over time, the more this factor negatively impacts rainfall variability. Therefore, the system notes three different scenarios on climate change until 2056: Low climate change (5%), medium climate change (10%) and high climate change (15%). In Annex IX, Figure 2A – F, one can see how this plays out on the water supply, the water gap following the proposed augmentation, under conditions of 'standard population growth'.

Solely focusing on desalination (by turning off all switches of the other forms of augmentation) is explored in multiple scenarios (Annex IX, Figure 3A – 3C) to see how desalination individually plays out on the water supply and demand system and water gap of the CCT. Parameters are set on 75 Megaliters of desalination, the current standard of 150 Megaliters and 300 megaliters. Following the graphs, one can see that the more desalinated water, the later the water gap would come about and the smaller the gap would be.

Decision point 2: Desalination placement

Since it is still not clear where the proposed desalination plant is going to be placed, the model accounts for the broadest decision points to give guidance on location. The model accounts for either the Benguela current or the Aguillas current. Most importantly, this choice feeds directly in the cost of desalinated water and subsequently, the Unit Reference Value over time. This, in turn, reflects to price elasticity which feeds back to the water demand. In Annex IX, Figure 4A - F, one can see the main effects placement in either the Aguillas or Benguela current has on respectively the total cost, the URV and the price effect.

Decision point 3: Timing

The timing of when to implement the desalination plant is to be regarded in the light of necessity. To install a desalination plant is trajectory with a delay of 3-4 years on average and is a multibillion Rand project. Ideally, this is covered by the national government in the form of financial backup. Nevertheless, to focus attention on water resilience, a looming crisis needs to visibly present for the government. Also, with advances of technology, the unit costs per produced ML of desalinated water are variable but almost certain to lower through time. Therefore, it is eminent to place this trajectory on the exact right time, where costs are lowest and possibilities for government backup are highest. In Annex IX, Figure 5A – F, the water gap is placed against the implementation of desalination on that apparent time, following from the water gap in Figure 1A - F – with the cost of desalination for that apparent timeframe reflected in the figures.

Decision point 4: Tariffs

In case of implementation of the proposed desalinated capacity, the government puts a burden on its citizens as they will see this reflected in increased water prices. As South Africa is a land with the highest up-to-date Gini-coefficient of the world (62.5 (CIA, 2013), ratio extremely rich to extremely poor; an index of 0% represents total equality and subsequently, 100% represents total inequality). An increase in the water pricing would have a rather devastating effect on the budget of the less fortunate. In the model, the government has a decision point in order to still maintain the desalinated water capacity, but to decrease its tariff to release the burden on the citizens. This is, only when the government is willing to invest in water structures without expecting a refund in the form of water taxes. The higher the tariffs, the lower impact of the effect of price elasticity. Following the model, arguments can be a double-edged blade: the higher the tariffs, the lower the burden on the government, but simultaneously a higher water demand as water is subject to the market. In Annex IX, Figure 6A, multiple government tariff scenarios and its effects on the water demand are captured.

Decision point 5: Fish / Coal Pricing

The government controls its (inter)national regulations on the price of fish and coal. To reduce coal and fish prices for pelagic fish species, this would reflect on the desalinated unit costs. Although adapting the entire fish price for the sake of lowering desalination seems rather unrealistic, the cost of coal can be adapted solely centered on desalination. In Annex IX, Figures 7A-D one can see how changes in fish prices and coal prices reflect on the operational cost (OPEX) of desalinated water over time, controlled for either the Benguela or Aguillas current.

6.2 Model in conversation

A “model in conversation” approach has been proposed for the exploratory process of model development. The method proved successful for the knowledge elicitation process from stakeholders – multiple quotes from stakeholders were noted down addressing the significance of combining sectors with each other and using a common ‘artefact’ or object for facilitated discussion. Introducing an interface to facilitate model insights for both technical and non-technical stakeholders also proved particularly useful.

6.2.1 Interpreting model and modelling process results in connection to literature

In relation to the literature used for this research, a large comparison can be made with the results of Blersch & Du Plessis (2014). In this research, the URV value for a desalinated unit approached around 15 rand per megaliter, which is approximately the same in current research. Costs are closely related to the estimations by the GreenCape (2018), whereas the Water Outlook Report also supports the target unit costs of the model. For conceptualization, the model drew from the findings of Musango et al. (2012), whereas the model shows a discrepancy in focus on supply demand programs. The Causal Loop Diagram of Musango et al. (2012) combined both demand and supply in programs to receive added water, whereas this research focuses to an in-depth analysis on these methods. The sentiment analysis of Joubert et al. (2003) was supported in conversations with stakeholders, adapting nearly the same variables to be of priority in the CCT. Similar to Sahin et al. (2016), the research found a double impact on water pricing through more expensive matters of water augmentation; higher supply and lower demand. Furthermore, environmental costs are in line with the brine dispersion rates of Sadwhani et al. (2005). In short term assessments, dropping fish species levels seemed to be not too much of a problem (SRK, 2007) whereas this systematic analysis predicts a stronger effect than initially calculated. Reasoning for this could be that the brine discharge is considered a stock in the model, thus, an accumulation. Fish would subsequently have a smaller pool to reproduce, hence there are less fish to be caught. For stakeholder engagement, the interface provided multiple positive responses, similar to the reporting of stakeholder engagement in the AWARD work of Clifford-Holmes et al. (2017). Lastly, in participatory modeling, the framework of Slinger et al. (2008) was followed. The procedure proved most effective for this research. In the form of model use and model implementation, it is still fairly early to see actual implementation of the model, although multiple stakeholders replied to see major usefulness in the model for further development.

6.2.2 Boundary objects

"One can achieve only a degree of confidence in a model that is a compromise between adequacy and the time and cost of further improvement." (Forrester, 1970). This quote could function as silver lining on the ACTDesal project. The project was of limited time, resources and infrastructure. Nevertheless, the attempt was made to make the model as detailed as possible with the time and resources available for the certain timeframe.

Since this model is one of the first exploratory frameworks via the method of System Dynamics on the water supply and demand system of Cape Town, the model was relatively limited within the reach of implementation. In an ideal situation, the model has enough time, resources and people available. The research aims to get the most out of both the model building process and model use process. The model building process had its major limitations in the quest for data. It is interesting and simultaneously raising concern how difficult it has been to get to any form of data or reporting qualitatively and quantitatively concerning the proposed desalination plant in Cape Town. This proposed desalination is a matter of billions of Rand, and yet everyone, including the people that work in the field is aiming in the dark. Without proper data the confidence in the model could be an obstruction in the model use phase. In the model use process, one is effectively evaluating how do people see something and afterwards, one can develop some form consensus by for example drawing a behavior over time graph with the stakeholders and letting them witness that this aligns with how the model corresponds to the change in behavior. Nonetheless, as the data is rather 'imperfect', the model might only correspond to the general line of argument and might be proxied too much. This can then cause a sense of distrust in the model which would be a major obstruction and limitation in its use and implementation.

A second, major limitation was of infrastructural nature. The time for fieldwork in South Africa was only 10 weeks and since the CCT gained international media attention with the recent drought, infrastructural coordination deemed to be very difficult. Researchers and government officials seemed in need of prioritization of their agendas, which caused many negative responses to the gathering of possible stakeholders.

As the model progressed, it became clear that time restrictions would force the model to keep to a fairly general level; as the period was a critical period and the CCT gained international media presence through the drought, water consultants had limited agendas and had to prioritize their time to relevance. Additionally, it became clear that the matter of finance was a hard one to find. As previously mentioned, the government put out a fund of 2 billion rand for water sanitation in the CCT, but the management of these financial funds remains yet unknown. Both directors of the water departments in Cape Town University, Kevin Winter, and Stellenbosch, Willem DeClerq, urge for clarification on where this funding is being monitored. As this sensitive factor remains unknown, together with the new development that private investors are stepping in to augmentation of the city, this makes the argument of why not to trace the source of financial aspects within the boundary of the model. The research deemed it more interesting to investigate the further effects of the augmentation measures themselves, keeping funding out of play.

Additionally, over the course of the fieldwork it became clear that there was an urgency towards a representation of the whole water supply and demand system and an exploration on its interdependencies rather than solely focusing on how desalination would play out. Therefore, stakeholder selection accounted for the both the technical and financial aspects of the augmentation measure, the environmental impacts involved and its socio-economic pricing effects.

Also, speaking with stakeholders has still rendered an incomplete, unrepresentative picture of the dynamics within the water demand. Modelling the demand side is rather qualitative of nature since there is barely any information available on quantifiable variables; therefore, a more detailed model of the demand sector has only been created artificially for the sake of visualization. To represent the dynamics of the demand system, one has to take a large leap to gain confidence in the model whereas the time spent with stakeholders was found to be insufficient – multiple critical parts of the model to represent the demand side were searched for in the interview, but a unanimous answer was not yet found due to limited time and infrastructure.

6.2.3 Participatory modelling and the 'model in conversation' design

This research was designed as a modelling in conversation process: the strive was to learn with and promote learning by affected stakeholders through the creation of a shared reality in the form of a System Dynamics model as a common denominator. In Participatory Modelling, a modelling procedure that is a purposeful learning process for decision-making which engages the ex- and implicit knowledge basis of stakeholders in order to create a formalized and shared representation of the reality. In this form of Participatory Modelling, the conversational input would simultaneously advance the quality of the model and help the stakeholders by seeing the model and getting explained what has been achieved 'with the input of other affected stakeholders'. Stakeholders would be able to dive into other expertise (for example, the marine environment) with the model as common denominator. This would expand their mental models: the model in this regard functions as an educational tool that has been agreed on by multiple professions. The outcome of these measures was therefore to be judged by the amount of positive messages that were provided and recognition for the justness of the model.

In several conversations, the need of a participatory model was explicitly mentioned to be a good fit for the problem, as some of the stakeholders claimed 'not to know too much of the details of desalination' for example. They claimed the model could help in providing them quick insight on the processes going on in desalination. Additionally, this was supported by messages as 'I think this research hits a bulls-eye in regard to what water management needs nowadays; a broad, communicative overview that is understandable for both the non-technical and technical stakeholders.' (Winter, 2018). Other, more technical stakeholders commented that the model 'hits the right fit with communication. Not too difficult, and easy to use' (Botha, 2018). All stakeholders declared that they wanted to be notified in the advances of the model and were interested in its further results. To this extent, the procedure and materials prepared for engaging stakeholders in the 'model in conversation' approach add empirical evidence to the value of engaging stakeholders in a System Dynamics modelling process. Particularly in contexts were group workshops are not possible to be implemented, a procedure such as the one adopted in this study showed its usefulness in the model conceptualization and formalization stages.

6.2.4 Process outcomes

The most direct outcome of the process was the introduction to systems thinking for multiple of the stakeholders. In the conversation, comments as 'I did not know that an increased water price would have such an impact on the economic situation of society' (P. van Heerden, 2018) and "It is great to see the combination to other expert fields. We usually do not have any contact with these professionals" (Winter, 2018) would indicate the positive outcome of the process of interviews. The process was specifically designed to give stakeholders a short and concise introduction on systems thinking by firstly explaining the approach, ways the model was developed, and an in-depth overview of the model. Stakeholders got to interact indirectly with each other through the model; it was the common denominator in imposing ideas for other fields and expertise.

6.3 Impact

Both direct and indirect outcomes of the research are proposed. An overview of the possible opportunities for the way forward, and the area this research might be able to expand in, is described in detail below.

6.3.1 Direct outcomes

A part of the development of the work manifests in active interaction with the University of Cape Town. As a result of seeing the model and interface, the director of the University of Cape Town's Future Water Institute endorsed the model for teaching and proposed a short course to the Future Water Institute on the basis of the model and the associated modelling work. The interface has proven useful as phrases as 'I saw the model but that was a bit too technical, but I understand why you did the things you did seeing the interface now' (van Heerden, 2018) and 'The interface really helps visualizing and communicating the model' (Winter, 2018) were commented when engaging with the model interface. The total representation of the interface is to be found in Annex V.

6.3.2 Opportunities going forward

Two postdoctoral fellows at the African Climate & Development Initiative (ACDI) at UCT are currently exploring options for furthering the work, in collaboration with Dr. Clifford-Holmes, Dr. Winter and others. Simultaneously, opportunities for research Masters theses have been opened on the Stellenbosch University in the form of a expansion to the ACTDesal framework by using System Dynamics. Both the directors of the water institutes of University of Cape Town and Stellenbosch University endorsed the research, making it a solid foundation for further opportunities. Due to multiple requests by stakeholders, the model and interface has been put online on the isee Systems website, making the research visible to be picked up by the affected stakeholders. Additionally, a collective short paper of the has been accepted and reviewed for the 6th Annual Conference of the System Dynamics Society: chapter South Africa (SASD), which is to be presented on the 22nd off November 2018. As mentioned before, a short course for the Future Water Institute had been proposed, which might be a foundation to push the ACTWater project forward. ACTDesal functions as a springboard to explore the applications and usefulness of System Dynamics on such a complex problem as water in the CCT and is therefore to be taken as a work in progress; the more time and resources available, the better the model becomes.

6.3.3 Areas for further research

Further applications and investigations of the model are yet to be explored; there are numerous possibilities to expand the model and continue on exploring the implications of for example groundwater or water re-use, and how this would affect the spectrum. Pushing the work forward can also be an investigation of a more in-depth nature: it might be interesting to further explore the most correct impact on the marine environment through desalination for example, by taking multiple marine organisms into account or investigating the dynamics of placing the plant within a 10 to 1000 meter range in the sea. Pumping costs are evidently higher by placing pumps further in the sea, but this might play out against a smaller fish revenue loss as the residue would likely be dispersing more effectively. It might be worth investigating which method of energy would be best suitable for the CCT by implementing this in the model – to explore whether sun-powered, water-powered or any other form of energy input would be best suitable. Costs can also be expanded with more specific data.

A further exploration on the demand side is a fair necessity in further progress where now only a qualitative example is produced (within the quantified model, demand is only captured drawn on the most essential dynamics on the demand side); the more clear the driving factors of demand, the more ease for the government to regard demand management programs.

In the proposed research Master theses for Stellenbosch University, a total of three different options were given to the students to choose from: (1) A preliminary assessment of environmental impacts of desalination on the Western Cape coastal systems and associated management and mitigation approaches, (2) A strategic assessment of surface water-groundwater interactions in the CCT and (3) Demand-side interventions at the household level.

7. Conclusions & Recommendations

In the research, the water supply and demand system of the CCT has been thoroughly investigated by making use of the System Dynamics methodology. In detail, an in-depth analysis has been performed on desalination. To have a final answer to the main research question, firstly the sub-questions ought to be answered.

1. '*How do additional costs of desalinated water add to the water price over time?'*

Through the in-depth analysis of the desalination model, the price is dependent on uncertainties in reduction through innovation and location of the proposed plant. It is a matter of operational, capital and environmental costs, which would differ through time. Subsequently, should the plant be installed in the Aguillas coast, the costs will be significantly reduced in relation to the placement in the Benguela coast in the long run. That is, if the management of the desalination plant is willing to take the credit for the loss in fishery revenue. For the part where costs are not governed by environmental instruments, through the Unit Reference Value, the price of the desalinated water is around 15 rand as opposed to the water price of 5 rand for distribution of freshwater from dam water sources. To place this higher water price in the bigger spectrum one should keep in mind that only a fairly small percentage of all water is being proposed to be through desalination (around 15% in current augmentation plans) – resulting in a desirable situation for the collective (less demand), but an undesirable situation for the individual taxpayer (higher prices) – especially in a development country as South Africa.

2. *How does desalination positively add to the economy of the city of Cape Town in the long run?*

Desalinated water takes the pressure off the water stress with an assurance of 100%: The problems of water would not be as apparent as they are now might desalination be implemented. Additionally, the model has shown to have a balancing effect on the water supply. In current augmentation plans for the CCT, price elasticity affects around 2% of the water demand. Therefore, desalinated water also balances water demand, which gives a 'double effect': on the one hand supply provision and on the other hand demand reduction. However, a higher water price raises concerns for the socio-economic situation: higher pricing would reduce the attractiveness of living in the city, which is crucial for people with a very low income. These people suffer the most from every price increase which then would affect their health as they cannot provide themselves with sufficient sanitation or drinking water. This other side of the coin, together with the socio-economic state of affairs is a trade-off the government needs to make; implementing desalination can be, although an effective solution for the collective of the CCT (as the city would have sufficient water which is relieving the domestic, agricultural and industry sector of a physical burden), a possibly crucial socio-economic burden on an individual, low-income level.

3. *What are the potential long-term effects of implementing permanent desalination on the marine environment?*

Although a question of importance, this research steered more to the costing function of the marine environment instead of the actual effects on the environment in detail. This is because stakeholders identified it to be of more importance to connect marine environment to finance instead of to effects to the marine environment itself; this had to do with the sensitivity of the subject, they identified money to be of higher importance for the sake of desalination than marine life. Through GIS mapping, a fish stock of pelagic fish has been created which is the most abundant fish species in both currents. The effect of brine residue, calculated per current and its subsequent dispersion rate, turns out to be more detrimental in the Benguela coast than the Aguillas. The model shows that in development over time, more fish will be infested in the sea (which can be taken as a rather short reasoning to assume that a fish population will keep on growing, but is in accordance with visions of experts (Lombard, 2018)). The more fish present, the more fish that can die prematurely due to brine residue. The more brine residue accumulates (within current calculations accounting up to 6000 ML of brine water at around 2045, controlling for the Benguela current) the heavier the effect is on the fish species.

4. To what extent are Participatory Modelling approaches useful to support water management decisions in complex scarcity contexts?

The 'modelling in conversation' approach of Participatory Modelling in the current context has proven to be of effective use because of multiple reasons. In conversation with stakeholders, multiple elements of the model were structured in a slightly different way as the literature suggested. The element of conversation tailored the model to the real-life situation of the CCT. The method of Participatory modelling also implied a mutual enhancement of mental models of the researchers and the stakeholders. In multiple comments of the stakeholders, as mentioned in Chapter 6, the stakeholders claimed the model to be of good use for expansion of their own knowledge basis. For the researchers, the method of Participatory modelling enhanced the model in quality by co-creating it to some extent with stakeholders as opposed to merely tapping information from a literature study. The element of visualization and engagement (the interface) was proven highly effective. All stakeholders argued their in-depth knowledge mostly after seeing the interface, which would give argument that the interface would make the model more tangible, comprehensive and useable.

All answers to the sub-questions provide guidance for a succinct answer to the main question:

"*In what way is the implementation of desalination in the City of Cape Town viable over a period of 50 years considering financial, socio-economic and environmental impacts?"*

Desalination seems to be viable for the long run, although a major investment has to be made by the government. The dangers this model identifies are the development of brine, the burden for low-income individuals and the cost involved for an increased assurance. It is therefore of utmost importance for the government to find the 'ideal' amount of desalinated water to avoid extremities in all these dangers.

Although the research covered much ground on the systemic analysis of long-term impacts of desalination in the CCT, there are still many ways in which the ACTWater project can proceed. A model is only as strong as the time, knowledge and resources available – whereas this has been no different for the ACTDesal model. Future possibilities are (amongst others) identified in the expansion of the model to an in-depth research of other methods of augmentation in the CCT, continuations on the investigations of impacts of the marine environment, exploring implications of possibly suitable methods of energy, or an in-depth investigation on systemizing demand management in the CCT. Although generally accepted and useful for current stakeholders, the model needs further development to tackle more angles of the water demand and supply spectrum to become a more solid framework for policy consultation and is therefore to be taken as a work in progress.

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Annexes

Annex I. Terminology

Water scarcity:

The excess of water demand over the available water supply.

Water stress:

The system symptoms expressing water scarcity or shortage, translated into e.g. the conflict that arises between water users, the downward trend in standards of water quality and harvest failures. Multiple circumstances due to water scarcity are covered by the term. (FAO, 2016)

Water shortage:

Low levels of the water supply as a result of insufficient resources or as a result of annual differences in climate. Water shortage is an absolute concept. (FAO, 2016)

Water gap:

A period of time where water demand is exceeding supply and therefore drains the (dam) water supply of the urban area.

Desalination:

The process of turning salt or brackish water into freshwater

Aquifer:

Underground natural storage basin containing groundwater

Runoff:

Runoff is the water from rain that did not absorb into the soil or evaporate, and flows into places that collect water, such as dams and rivers.

Non-revenue water:

Water that is being wasted through leakages in the water system.

Brine:

Water from desalination that is extracted from practically all nutrients, leaving a salty, non-nutritive form of water.

Installed capacity:

The number of units that have been installed – in this context, expressed in Megaliters.

Fish revenue gap:

the gap that is induced by the revenue of fish that should have been available in normal conditions

Precipitation :

The amount of water that is caught by the dam capacity.

Multiplier:

Parameter adjustment by additional percentage.

Annex II A. Stakeholders and their relevant points

NB: Meeting recordings available on request.

Kevin Winter (director FutureWater Institute, University of Cape Town)

Date: 26 April, 2018
Time: 10:00 – 12:00
Location: University of Cape Town
Invitees: K. Winter, J. Clifford-Holmes, T. Sluijs
Attendees: K. Winter, J. Clifford-Holmes, T. Sluijs

Goal/Purpose of Meeting:
Meeting 1, introduction on the subject; stakeholder analysis & snowballing; depicting relevance of System Dynamics, general conversation on water systems in Cape Town

Outcome of Meeting

Stakeholder snowballing:
Rolfe Eberhard - private consultant, civil engineer environment policy.
Peter Flower - director water sanitation city
John Frame - water demand management
Giesela Kieser - directorate of informal settlements and water.
Barry wood - Bulk Water
Xanthea Limberg – minister of water and infrastructure Cape Town
Arthur Weinberg - lawyer attorney on water pricing fighting. OUTA

High level notes:

Look at the assurance level of supply
The availability of money; Nobody knows who is controlling the government funding of 2 billion rand. The only hint the university has is that the document is written by the world bank; correspondence with America is needed.
Possibilities in desalination capacity: Desalination is eventually the solution to the problems with a 100% assurance of supply but is a trade-off

Date: May 3, 2018
Time: 10:00 – 12:00
Location: University of Cape Town
Invitees: K. Winter, J. Clifford-Holmes, T. Sluijs
Attendees: K. Winter, J. Clifford-Holmes, T. Sluijs

Goal/Purpose of Meeting:
Meeting 2, follow-up on meeting 1. Snowballing, progress, in-depth analysis.

Outcome of Meeting

High level input

Vantage point model: where do you physically see the water stress? So, your ratio. Is a great vantage point according to Kevin.

The location of the service is affecting the cost c.q. **cost attractiveness**.

Water supply service provider: the location is important for close to the sea or deeply in land. **Geographical** function to **service** provision.

Model input

Energy intensity: is because the water is on 0 above sealevel. Water that is higher up in the mountain is easy to distribute: that infers lower cost of distribution. Supplying the water at the point where it is needed is always going to be high in desalination because of energy intensive distribution cost. Elevation is key - the volume must equal the demand, but your demand needs a certain amount of energy. Direct relationship to the demand and the volume.

Energy requirements for dam capacity: You need to ask Kobus to get further in this. A hint: the Steenbras dam is on a mountain, other dam (name unknown) is down in cape town. With high demand (daytime), the water flows from the Steenbras dam. With low demand (nighttime) the water flows from the other dam to be most efficient in energy cost and water distribution. Real numbers are unknown by Kevin.

Licensing for farmers: Effective ways of getting along with water-> use only the most fruitful pieces of land. The farmers get the first cutdown on water demand and Willem argues that that is a wrong way of doing as the CT needs its agriculture for export. Right now, they are ‘only keeping the plants alive’.

Water for irrigation should require less cost as those locations are mostly flat; that means only 0-5 meters above sea level. Distribution of water should therefore be redistributed to the farmland to save the cost.

Date: 19 June 2018
Time: 10:00 – 12:00
Location: University of Cape Town
Invitees: K. Winter, J. Clifford-Holmes, T. Sluijs
Attendees: K. Winter, , J. Clifford-Holmes, T. Sluijs

Goal/Purpose of Meeting:
Meeting 3, continuation

Outcome of Meeting

Stakeholder snowball:
Tom pancreas -> independent desalination consultant

High level notes:
Report on desalination sustainability cape town (shared)
Info on small desal plants: these are very unsustainable as the membranes should be continuously introduced. When this does not happen, the desalination plant becomes extremely expensive as new membranes should

You have got to distinct between innovation, and innovation in the 'pipeline'. Technology that is state-of-the-art would not immediately be available for Cape Town .

Some opportunities for the CCT: cities pressure management: the CCT needs to change its pressure management system as this is an old technique. Kevin thinks the city needs to isolate the water strategically; the valves should be played with; getting less water out of the taps by reducing the bar levels.

- ➔ In systems perspective: this would be a high leverage, relatively low-cost parameter.

Model on two scales: strong way of representing the system
We are not particularly challenged by systems that are just representing a single aspect of desalination; we want to smear this out on the entirety of the system.

It is a question of timing: when do we install desal in the longevity of future advancements of desalination in term of cost reduction?

Groundwater flow would lead to peculation, base flow, infecting river runoff. -> paper. For Kevin , storm water management is a great step to add a cushion to a large-scale investment in water management. Can we have enough in our system to keep it running?

The city has been running its water demand management pretty well. The difficulty is the maintenance of this micromanagement. Desalination is a tough choice. Day zero pushing forward was just to scare the people; an effective form of managing water

Date 22 June 2018
Time: 11:00 – 11:45
Location: University of Cape Town
Invitees: K. Winter, J. Clifford-Holmes, T. Sluijs
Attendees: K. Winter, J. Clifford-Holmes, T. Sluijs

Goal/Purpose of Meeting:
Meeting 4, validation

Outcome of Meeting

Water demand management:
tweak on savviness – the government is not managing the education.
Within the regional context – talk about it within the boundaries of the city. We are sharing dams with farmlands (which is regional): this results in a polarized discussion. The distribution is going mainly to city. The city of cape town is highly dependent on the farmers – there is a large loop between irrigation but that is outside of the boundaries of the city context.

Government restriction: use this as government management.

Savviness: it should be rather water smartness.

Gradual buildup of the savviness (10-20%) would be correct.

The surface water is a combo – that is a good interplay.

A factor of lifestyle; the growth of the medium income is going to be higher. This poses a danger for the society. These households have a higher domestic water demand (as they can afford for example washing machines that are consuming a large amount of water).

<u>Willem de Clerq (director water institute, Stellenbosch University)</u>

Date: 4 may, 2018
Time: 10:00 – 11:45
Location: Stellenbosch University
Invitees: W. de Clerq, J. Clifford-Holmes, T. Sluijs
Attendees: W. de Clerq, J. Clifford-Holmes, T. Sluijs

Goal/Purpose of Meeting:
Meeting 1: introduction, stakeholder snowballing, first input

Outcome of Meeting
Possible **snowballing:**
Chris van Holdt
Catherine Blersch
AURECON Nico Rousseau

Water availability:
Agriculture is 70% of water globally: Cape town can get more income from irrigation.
We must redesign water distribution

The problem is we have to change the playing field before we can start on desalination.
This would be conceptualised into theory phase 1: The bigger picture.
Further scope of problem: Electricity is a hard constraint otherwise we could've just gotten water from other regions. We don't have enough electricity, it doesn't solve the problem of agriculture.
He argues that we have to redesign water redistribution and make the costeffectiveness of farming more viable:
It is 150.000 rand per month on electricity on middle and small scaled farms to irrigate.

Electricity production -> limitation, for small businesses are not able to keep up with

Medium size farm 60-88 farms pay 150.000 rand for electricity cost

Project is 5 years development plan
Limitation to get this working: indicate the shortcomings and what would be the burden to that to the taxpayer

Water supply: Cape Town is using 50% less water
Hence, the income generated from water is 50% less

The idea is to Get a pipeline running from the eastern cape to the western cape as this in terms of ecologic scarcity would be way less stress due to urbanization western cape, we can capture a lot more water that is overflowing from these small dams adding the water supply with an additional 30%. With the likes of DWS -> economically viable.

Propose how to make the playing field bigger to make sure how to afford all these options without making it more expensive

Agriculture generates the means to being able to afford water

Seem could provide for more agriculture als small farmer Ould be more able to start up their business. -> subsidised electricity could build up the scale which would allow more 70% is dependent on agriculture. A large part of that is export for global market - if the export market goes too Ould see a lot of those commercial farms collapse. Electricity is the largest inflation component!

Electricity is the biggest problem for desalination

Be careful not to propose something which would have no value as it doesn't fit in the playing field - FoodWaterEnergy Nexus

Date: 11 June, 2018
Time: 12:00 -13:00
Location: Stellenbosch University
Invitees: W. de Clerq, T. Sluijs
Attendees: W. de Clerq, T. Sluijs

Goal/Purpose of Meeting:
Meeting 2. Continuation on meeting 1; expert input and validation on model.

Outcome of Meeting

Meeting notes

Energy requirements	Water volume is divided to water from mountain (700M) and water from purification (0M)-> allocation to lower area, balance in distribution
	Theewaterskloof 12x catchment size **How much water is needed at what elevation?** CPT 10 – 200 m above sea-level
Environmental flow requirement	Percentage of the annual extraction from these systems
	Priorities: licensing. Access to water -> in terms of need: 1. Personal access 2. Agriculture (license) 3. Industry

<u>GreenCape (NGO, sustainability Cape Town, creation of Water Outlook Report)</u>

Date: 10 May, 2018
Time: 15:00 – 16:00
Location: GreenCape, Cape Town
Invitees: GreenCape, J. Clifford-Holmes, T. Sluijs
Attendees: R. Kruger, T. Sluijs

Goal/Purpose of Meeting:
Explanation of Water Outlook report, feedback on model, supply options for Cape Town

Outcome of Meeting
High Level Notes :
Desalination project is run as a city project, whilst the mandate has to come from the national authority.
The city wants water security to keep the people happy.
Desalination scenario's internally done by the city.
The model is as good as its input - where do you place yourself? Is this going to be from a multifaceted viewpoint or is it going to be an academic viewpoint which you are going to send around? -> Reply: within model boundary high level 'rough sketch'. Through time and development, more of a multifaceted input, now still more academic in phase.

Reasoning / ideas:
Reasoning behind private investment to step in and provide own desalination plant:
The calculated cost for these companies in a risk analysis would be too high to just wait for the govt to build the additional desalination (36 months) as they think they and do this faster and avoid the day zero drought of next year.
-> their economic value would be higher than the government can provide in these financial terms.
GreenCape does not have the numbers on this.
Temp desalination is not viable says the world bank.

Model input:

- There is no consolidated data on the percentage of private investment
- 120 MLD at 12rand/KL
- The city is now considering ONE desalination plant of 120-150 ML on behalf of the World Bank
- The need for water augmentation is 200 MLD on a 20y frame whereas the city is now aiming at 370 MLD augmentation
- The city is aiming at maximizing the cheapest options first and then desalination (water reuse, surface water etc.)
- Reasoning for 120-150 MLD optimum: The water that can be obtained through river runoff is still way higher. You cannot completely move away from rainfall, in terms of cost viability. Look at the water outlook report. In a timespan of 50 years rain is projected to be 10% less - which still would mean that the city can rely on their dams as river runoff is about 7x as high as its demand. This means you cannot overcapitalize on desalination: the economic impacts would overshoot. This would then become a liability for the government (mothball) rather than a solution.

<u>Kobus du Plessis (Prof. Dr. Engineering, Stellenbosch University)</u>

Date: 11 June, 2018
Time: 13:00 – 15:20
Location: Stellenbosch University
Invitees: K. du Plessis, T. Sluijs
Attendees: K. du Plessis, T. Sluijs

Goal/Purpose of Meeting:
Expert input on the technical side of desalination; clarification of articles and URV's (Du Plessis, 2007; Blersch & Du Plessis, 2014); model verification from desalination expert.

Outcome of Meeting

Stochastic sequences	98% recurrence interval: testing 200-600 reliabilities of supplies – 2 years can be 'off-limit' in 100-year time frame
	Median value taken for URV
Funding	Although legally the state, in these cases most likely municipal cost
	➔ return of value per cubic m3 has to be viable. Cost desal water 150 ML R15.83
Environmental flow requirements:	Minimum percentage value- > differs for the initial amount in the dam.
	➔ I'd say model 2 different streams: Theewaterskloof and 'other'
Failure rate	no failure rate on this big of a plant
URV	Reasoning: different time scales for different augmentation matters.
	Book: a guide for desalination (Kobus shared it) is still on point.
	URV is value of all form desal included- so maintenance AND initial cost.

Mandy Lombard (Prof. Dr. Marine Environment, Sedgefield)

Date 27 May, 2018
Time: 14:00 – 15:30
Location: Skype
Invitees: M. Lombard, T. Sluijs
Attendees: M. Lombard, T. Sluijs

Goal/Purpose of Meeting:
Expert input on the marine environment in relation to desalination.

Outcome of Meeting

Brine	Tides
	2 scenarios: Aguillas. Benguela
Considerations	Tides, mixing Salinity & impact of salinity
	Impact on fisheries
	Energy costs of water drains
	Off-shore distance
	Density decay
	Sensitive areas, dies

<u>Water4capetown (NGO, civil rights organization Cape Town)</u>

Date: 30 May, 2018
Time: 13:00 – 14:30
Location: Cape Town
Invitees: Water4CapeTown, J. Clifford-Holmes, T. Sluijs
Attendees: P. van Heerden, T. Sluijs

Goal/Purpose of Meeting:
Expert input on the water demand side.

Outcome of Meeting

Tourism facts	2017: 30% drop in tourism 2018: 40% drop in tourism
Pricing	water prices are up 40% since last year
Water reuse	Water reuse in Israel – 11x (1100%). in cape town that is 10%.
	25% of the sewage plants (for water reuse) is in an unusable state.
infrastructure	37% of water supply is lost underway due to bad infrastructure
demand	COMMUNITY DROUGHT PLAN THROUGH WATER SAVINESS.
	➔ Mass media sources mere exposure effect.

Andries Botha, PhD. (System Dynamics entrepreneur – water systems, senior Toyota Group South Africa)

Date 14 June, 2018
Time: 14:30 – 16:20
Location: Johannesburg
Invitees: A. Botha, J. Clifford-Holmes, T. Sluijs
Attendees: A. Botha, J. Clifford-Holmes, T. Sluijs

Goal/Purpose of Meeting:
Technical viewpoint on model, model verification

Outcome of Meeting

Andries is a System Dynamics entrepreneur having worked in the water field for several years, and is therefore very familiar with the mapping of water systems in system dynamics.

High level notes

Proposition: model the entire water model of CCT.

Work with multiplier, is good on the water stress

Water reuse is water demand

Several techniques to be used as to be seen in the images

For depletion of groundwater, build a stock that depletes

Delay factoring in on water coming in

Desalination coming in, desired vs actual is an excellent choice

‘Sustainable city’ as a pitch

Presentation to some of Andries’ contacts

Brine dispersion in a pipeline delay with elements coming out

Graph on developments over time

URV should be calculated according to the methods.

Rainfall scenarios as NORMAL is a good choice as well

Investment of government? Not sure

Try and incorporate more clear line of argument

<u>Paul Currie, PhD (water system dynamics engineer / research fellow, Stellenbosch University)</u>

Date: 24 June 2018
Time: 20:00- 21:00
Location: Greenpoint, Cape Town
Invitees: P. Currie, T. Sluijs
Attendees: P.Currie, T. Sluijs

Goal/Purpose of Meeting:
Technical discussion on the model

Outcome of Meeting

Exceptional result for desalination: guaranteed water means we can massively decrease the water increase

Data help:

- ➔ Demand structures.
- ➔ Breaking it into three groups: low middle and high income -> estimates
- ➔ Domestic is largest one

Disaggregated level: **income groups**

You can get demographics on population through the averages of the income cohorts.

THEN: for 2012 2013 2014 2015 2016: on the suburbs can assign that proportion of consumption to that. -> PhD

Combined consumption

KL per day – water use types.

Property values per square footage. That could be used as viable measurements.

Detailed on consumption:

What you need is how much each cohort produces and what the effects of tariffs are on these cohorts per income group.
You can also just make the assumption that people respond well to the restrictions. You can talk about a blanket percentage reduction. -> blanket by 10 percent
Acknowledges that there have to be made many assumptions, water demand is very qualitative
Suggested income can be taken more general and cut down in only one group.

Restrictions:

water was restricted to 190 KL per day -> these are **Step tariffs**
Restrictions are necessary to get personally invested: Currie thinks that water is always in a restriction level in Cape Town.
It is all about timing: when do you invest in the infrastructure? When the need is high. That is now.

Water supply -> Paul worked on water re-use himself.

3 groups price elasticity on water restrictions

More interesting: how much reuse is necessary to make up to the standards of potable water? -> experimental case Atlantis -> figure out on percentages to distribution canals

Total water available -> greywater/ freshwater?

Available water should be a stock – dam water does **NOT** have to be a stock -> if its sole purpose is informative then do not bring it in

Article on the relations of water demand behavior and the news articles exponentially growing

Article on 77% of water supply is from DWS

Water balance 2015: the amount of water that was <u>purchased</u>. Total water demand 288 278 etc. in 2015 total water supply: 296 254.

<u>Dr. Rod McDonald (lecturer Systems Thinking, Virginia State University)</u>

Date: 8 august, 2018
Time: 14:10 -14:40 & 18:00-18:45
Location: Reykjavik, Iceland
Invitees: R. McDonald, T. Sluijs
Attendees: R. McDonald, T. Sluijs

Goal/Purpose of Meeting:
Technical input on model

Outcome of Meeting

Overall model constructed very well; how to reduce water to the dam level restrictions is by capturing overflow. This can be captured as effect.

Circularity because of a single stock; quick fix.

Form of water supplied instead of water demand as outflow as it is a pipeline capturing the backlog. Sent to B. Schoenberg of iSee systems; introduced MIN function.

Modeling rainfall in NORMAL function is interesting way of doing, yet gives you a major disadvantage in capturing the system as it is a lot of disturbance. You should make a trade-off.

Annex II B. Total time planning in fieldwork

13-03	Information alignment	Feedback session with supervisor & project leader
20-03	2^{nd} draft version literature review	
20-03 / 27-03	Working on revision literature review, first start at conceptual model	
27-03 / 30 -03	Going over the model	Putting up conceptual models with Jai Clifford-Holmes in NL
30-03 / 6-04	Perfecting conceptual model	
6-4	Second draft conceptual model	Feedback with supervision
6-4 / 14-4	Finishing conceptual model, Going over literature review	
15-4 / 20-4	Settling in	Cape Town transfer
28-4	Information gathering	Session Kevin Winter
31-4 / 3–5	Post- and pre-processing	Aligning info with model, prep for new session stakeholder and feedback with Jai Preparing prezi
3-5	Information gathering	Second session Kevin Winter
3-5 / 4–5	Post- and pre-processing	
4-5	Information gathering	Stellenbosch University stakeholder sessions
5-5/8-5	End of work week	Setting model boundary, scoping phase done
8-5 / 11-5	Information gathering	Model boundary done, adjusted version of

		introduction, meeting R. Kruger
11-5 / 13-5	Stakeholder engagement	Meetings at UCT
14-5- 17-5	Stakeholder snowball	Working on input from Stellenbosch
17-5/ 21-5	Model construction	Small sub models work
21-5 / 24-5	Model setting	Workshops in George – validating the model
25-5/27-5	Meetings	Meeting Kevin Winter, Mandy Lombard
27-5 /30 – 5	Process analysis- model construct	Modelling
30/5 – 3/6	Stakeholder meetings	Meeting water4capetown
3/6- 6/6	Post-processing	Model construction on basis of new input
8/6- 10/6	Mode construction	Post processing, incorporation of model (together with P. Currie)
10/6- 11/6	Stakeholder meetings	Last stakeholder meetings before going to Johannesburg
12/6- 16/6	Validation	Model validation in Johannesburg, collaboration with A. Botha
20/6-25/6	Model validation	Multiple stakeholders conversation, validation sessions with K. Winter, P. van Heerden, P. Currie

Annex III A. Variable focus

ACTdesal model
-Assessment of Cape Town Desalination

Variable focus:

	Endogenous CRITICAL	**endogenous LOOSE**	**exogenous OUTSIDE**	**stakeholder ENGAGEMENT**
Environmental impact	Brine discharge Chemical disposal Currents behavior Brine density Environmental cost marine impact	Location of desalination plant Transport requirements & emissions for transport biodiversity in areas of scenarios salinity of area	Innovation techniques (regard: freezewater distillation, State of the Art membrane techniques Edies Overall reduction through less water stress (energy wise)	Name: Prof. Dr. Mandy Lombard Expertise: Marine Biology Name: Marine Biology group Sedgefield (Short Course facilitation 18-23 May) Expertise: various PhD, Post-doc, doctorates in (marine) environment
Desalination pricing	Price elasticity water demand Unit reference value	Government subsidy options Legal obligations government	Normal water pricing	Name: Dr. Rolfe Eberhard Expertise: urban water pricing (independent Consultant) Name: Prof. Dr. Kobus Du Plessis Expertise: Civil Engineering (SSU)

Water demand	Domestic use of water	Water licensing Water used for irrigation Population in-/outmigration City attractiveness (water scarcity effects on) tourism & in-migration Water savviness	Population Birth/death rates Water used for mining, industry	Name: Suraya Scheba Expertise: PhD on socio-economic perspective desalination 2016 (Sedgefield) Name: Paulette van Heerden (Water4CapeTown) Expertise: public opinion
Water supply	Desalinated water supply	Water reuse supply, expansion opportunity & instalment time Groundwater supply, expansion opportunity & instalment time Dam supply, expansion opportunity & instalment time Evaporation and precipitation	Rainfall patterns Environmental flow requirements	Name: CSAG (Climate System Analysis Group, University of Cape Town Expertise: Hydrology Name: Willem de Clercq Expertise: Water Supply Systems Western Cape (director of water institute Stellenbosch University)

Desalinated cost	Reverse osmosis (direct numbers on cost) Installment costs Variable costs	opportunities on solar energy extraction opportunities on wind energy extraction	Employment cost desalination	Name: Prof. Dr. Kobus Du Plessis Expertise: Civil Engineering Name: Dr. Steven Mallory Expertise: Desalination Mossel Bay
Economy	Water effects	Individual price elasticity	Development opportunity because of water availability Overall employment opportunities (f.e. hotel personnel) rising through 120 mL desalination -time saved for water fetching	Name: Paulette van Heerden (Water4CapeTown - activist group) Expertise: water demand, public opinion
Desalination decision making	Assurance level of supply Availability of money Government Subsidies Possibilities in desalination capacity	Investments in public programs		Name: Dr. Kevin Winter Expertise: director of Water Department University of Cape Town Name: Raldo Kruger, GreenCape Expertise: legality on decisions –

				creation of Water Outlook Report (GreenCape NGO)
Time delays	Desalination (region specific) building delays Funding models	Brine residue time delay		Name: Willem de Clercq Expertise: Water Supply Systems Western Cape (director of water institute Stellenbosch University)

Annex III B. Concept note

A model-based exploratory analysis of desalination options and opportunities to tackle the drought crisis in the City of Cape Town

Teun Sluijs | project summary

teun_sluijs@hotmail.com https://www.linkedin.com/in/teun-sluijs/

Executive summary:

This concept note introduces a research programme that explores the dynamics and the financial, socio-economic and environmental implications of including desalination in the water supply mix of the City of Cape Town. The action research project employs System Dynamics modelling (SD), a form of systems analysis, to assess the city's short- and long-term desalination strategies in order to develop an interactive decision support platform that is useful to both technical and non-technical stakeholders in Cape Town.

Background:

As of March 27 2018, the water levels of the main supply dams for the City of Cape Town (CCT) were at 22.0% of their total capacity (CTnews, 2018). Multiple projections have been made on the dam levels for the upcoming months, pushing the deadline for 'Day Zero' back and forth (Capetownnews, 2018; Capetown.gov, 2018). On Day Zero, the day the taps in the city are portrayed as 'running dry', the reticulation network will be severely restricted with residents constrained to a daily ration of 25 liters of drinking water/person/day.

As water demands continue to grow, CCT is one of the South African coastal cities that are considering desalination as a potential future water supply source. Desalination is different from conventional surface and groundwater supply sources in that it is climate-resilient, having an assurance of supply of essentially 100 percent. However, the increased reliability comes at a cost. This research explores the multiple costs and benefits in their interdependent forms:

1. The financial cost of installing a permanent desalination plant using reverse osmosis (RO) is projected to cost around R 2 Billion. The SD model will provide a cost-benefit analysis disaggregated into national, provincial, and local government by looking holistically at the capital and operational costs under different scenarios (*e.g.* desalination for providing a constant base supply versus mere intermittent emergency water provision).
2. Possible socio-economic impacts, including new job trajectories, health impacts resolving from the lack of water, water competition, etc.
3. Environmental impacts: desalination plants produce by-products that can be harmful to sensitive marine ecosystems. In addition, RO is an energy-intensive process with associated greenhouse gas emissions.

About the method:

System Dynamics (SD) is an approach to understanding the behavior of complex systems over time. It captures internal feedback loops and time delays that affect the entire system. Developed by Prof. Jay Forrester at MIT in the 1960s and popularized by the Club of Rome's *Limits to Growth* in the 1970s, System Dynamics has been successfully applied to study demographics, economic growth, business development, water and natural resources management, and environmental systems. Its capabilities to quantitatively simulate the dynamic consequences of various policies make it an ideal decision support tool for strategic policy testing and selection, especially for complex problems such as working out when and at what scale to implement permanent desalination in the CCT. The graphical form of modelling is appropriate for engaging stakeholders, both those technically and non-technically inclined.

The research:

To gather the information needed for building the SD model, fieldwork in the form of region-specific data collection is needed, which will form the basis of the stakeholder engagement. Therefore, from April 15 – June 15 2018, research will be conducted under the lead of Dr. Jai Clifford-Holmes (Institute for Water Research, Rhodes University) and Dr. Nuno Videira (Nova University Lisbon, Portugal) through the program of the European Master in System Dynamics (EMSD)[3], in collaboration with water

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[3] http://europeansystemdynamics.eu/

researchers at the universities of Cape Town and Stellenbosch, government officials (National Treasury, Western Cape provincial government and municipal officials and committees), engineers and environmental specialists on desalination, affected communities such as ratepayers' associations / OUTA lobbyists, civil society groups, and private funders.

By exploring the addition of desalination into the water supply augmentation mix in a holistic manner, this research will help stakeholders in two primary ways: firstly, involvement in the model-building process will **increase their own knowledge basis** in strategic decision-making in water desalination. Secondly, the potential model outcomes will result in **long-term risk reduction** under certain scenarios. It has the potential to become a mutually agreed protocol that investigates major possible scenarios; participatory system dynamics is an effective approach for bridging gaps between disciplines and sectors, which can help provide analytical support for strategic decision-making on desalination.

For further information:
Please contact Mr. Teun Sluijs on teun_sluijs@hotmail.com or +27(0)76 019 6263; alternatively, Dr. Jai Clifford-Holmes on jai.clifford.holmes@gmail.com or +27(0)82 769 1622.

Annex IV. Process briefing

An overview of ACTdesal:

The <u>A</u>ssessment of <u>C</u>ape <u>T</u>own's long-term Desalination

What?

ACTdesal is a collaborative effort between multiple stakeholders that explores the financial, socio-economic and environmental implications of including desalination in the water supply mix of the City of Cape Town making use of a method called System Dynamics.

Who?

The process of *ACTdesal* is an initiative of **Dr. Jai-Clifford Holmes** (Institute for Water Research, Rhodes University), in alliance with the **Erasmus Mundus European Programme in System Dynamics** – an international collaboration between Radboud University Nijmegen, the University of Bergen and Nova University Lisbon in the practice of System Dynamics- represented by a Dutch lead modeler Mr. Teun Sluijs (Radboud University, Nijmegen) under the supervision of Dr. Nuno Videira (Nova University, Lisbon).

When?

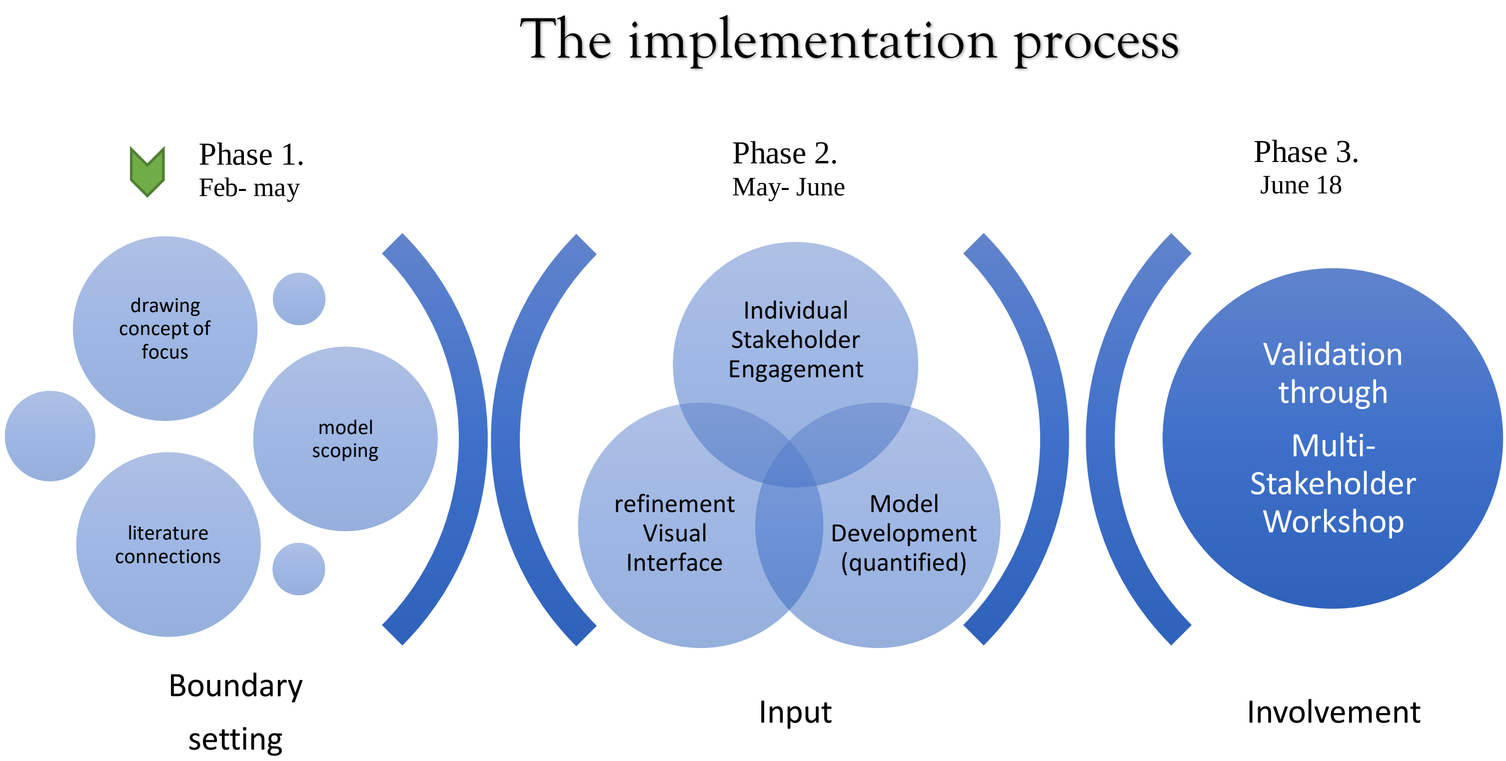
The projected running time of the project currently resides on the period of **February 2018 – July 2018.**

Why?

Our <u>aim</u> is to use the System Dynamics modelling language as a **common** denominator to set a **common** ground for **common** understanding between available expertise within researchers at the universities of Cape Town and Stellenbosch, government officials (National Treasury, Western Cape provincial government and municipal officials and committees), engineers and environmental specialists on desalination, affected communities such as ratepayers' associations / OUTA lobbyists, civil society groups, and private funders.

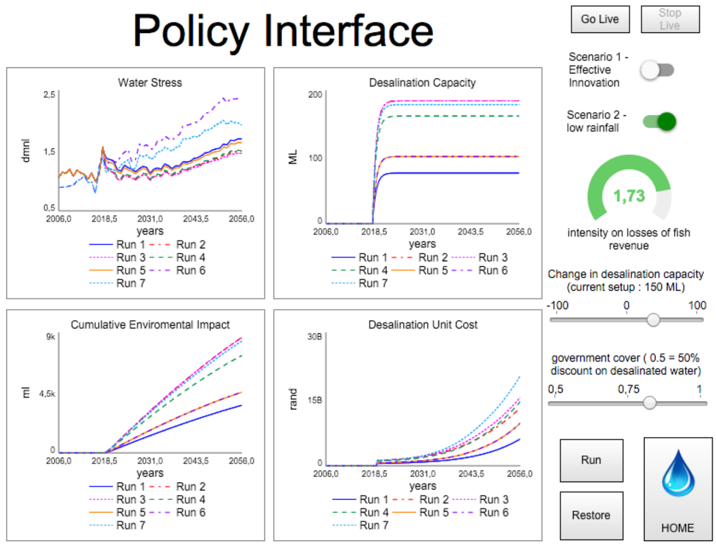
Which purpose?

Our <u>goal</u> is to **achieve** a **better holistic understanding** and **improve the decision-making quality** of (the incentives of) long-term desalination by creating visual interface that can help as a decision-support tool useable for both technical and non-technical stakeholders with an underlying model driving this interface. We wish to **create a collaborative agreement** on long-term desalination. The challenge of desalination is an interdisciplinary, uncertain one, whereas climate change imposes further challenges, especially for a climate reliant city as Cape Town - stressing the need of rigorous measures as desalination and attempt to reduce this uncertainty to essentially zero. Interrelationships between variables and cause-effect feedbacks over time are central to the method, whereas in desalination intersectional expert input is needed to capture the behavior with the right reasoning. Capturing this behavior would make up for a foresight in the future; As we know how desalination establishes in current conditions and trends, we would be able to estimate its behavior over the upcoming time. In essence, this research would itself the question: **"What are the underlying factors driving new long-term desalination in Cape Town?"**



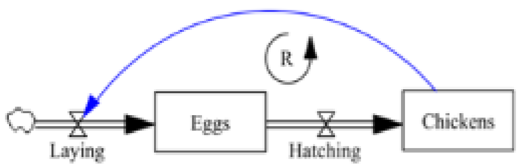
Phase 1 – Boundary setting

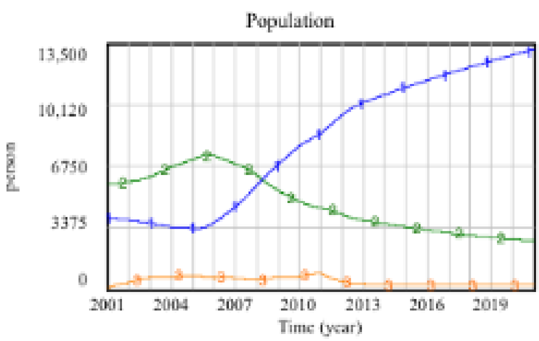
Within this phase, the problem is being analyzed as well as the boundary of the model. The phase is about prioritization of the model variables considered to analyze the **financial, socio-economic** and **environmental** situation: *One can model the whole technical process of desalination, the only question that remains is whether this would add to the aimed outcomes*. By making causal loop diagrams, which are overviews of relationships in desalination flowing from an extensive literature review (how **we** think the model should be constructed), a first model draft based on a theoretical framework is provided.



Phase 2 – Input

In phase two, stakeholder engagement is prioritized. Through conversations with multiple stakeholders from multiple fields, the model will be provided with expert input over different expertise (How **you** think the model should be constructed). A collection of thoughts on structure will be taken into the model, providing a qualitative basis for the reasoning behind the model. Subsequently, the model shall be quantified in the form of a stock and flow diagram – on the basis of differential equations, this would provide a mathematical logic behind the model.



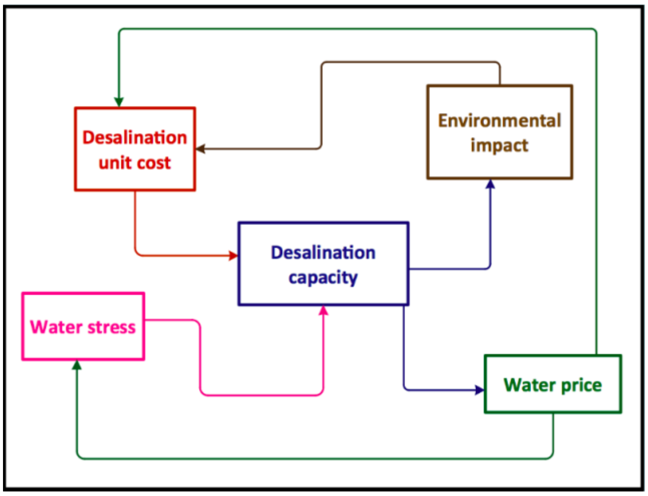


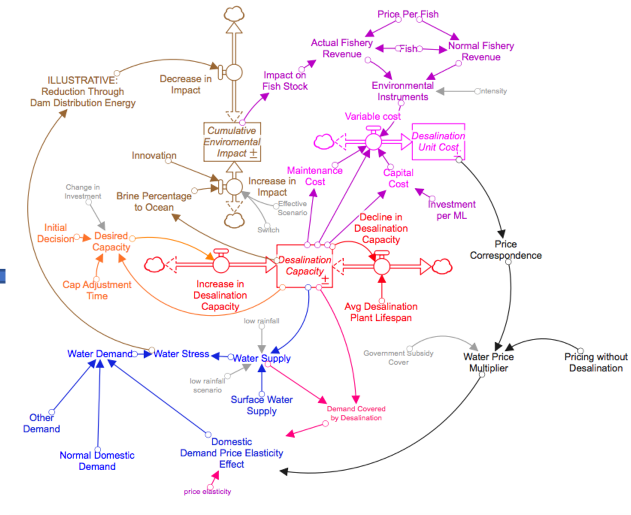
Phase 3 - Involvement

On the 19th of June 2018, a multi-stakeholder session will be held with individual representation of various different sectors in order to validate the model. The model will contain a visual interface, which would allow the stakeholders to see impacts for the suggestions they made. In the stakeholder engagement session, the model receives validation through interdisciplinary dialogue; how **researchers and stakeholders** agree how the model should be constructed. By simulating different scenario's and policies, we can learn more about the dynamic implications the addition of desalination infers (i.e. how the need would change over time and the finding of appropriate responses to the change in conditions).

Model Synthesis – The reasoning

The central variable of this model is the capacity of desalination, which is being impacted by the cost of the unit and the interplay between water demand and water supply. The more stress, the more need for desalination; the higher the cost, the less need for desalination. The model would investigate the exact influence over time on the added water price for desalinated water, resulting in a lower water demand, hence lower water stress. Simultaneously, as desalination capacity increases the amount of brine would accumulate, resulting in a higher cost for companies in compliance with ecologic standards. In- depth sub-modelling and levers for change are to be included on the basis of shared insight.





Project aims

1. **Achieving a better holistic understanding**

   ACTdesal represents connections among factors affecting different stakeholder in a transparent matter. Whereas the human mind fails to think beyond a total of two causal relationships, the *ACTdesal* model can get beyond these obstructions and provides a logical structure to the problem.

2. **Improving decision-making quality of stakeholders through scenario-building**

Visualization of aspect we find to be key; communication of the model will be represented in scenario-building which is a product argued by stakeholders, connected by researchers. The model can justify and provide background reasoning on the decision which has to be made through different scenario's (e.g. the investment in a desalination plant), as the model gives a visual representation of the consequences.

3. **A collaborative agreement on desalination**

As the model is a collaborative product by, and for, stakeholders in desalination, individuals can relate to the represented variables. As simulation runs are presented and interconnections validated, *ACTdesal* facilitates the development of a shared mental picture. This can, in turn, improve stakeholder communication across sectors and helps assist in future planning activities.

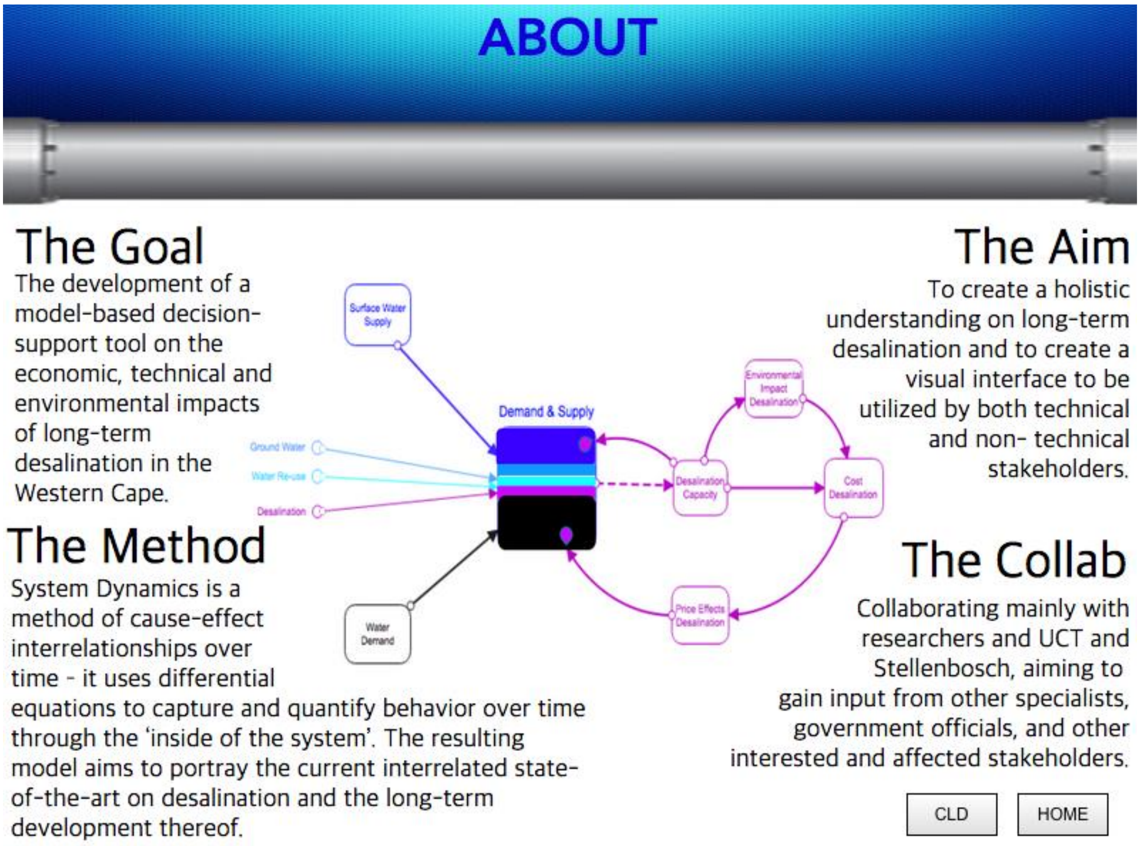
The model can bridge the gap between disciplines and sectors, which brings a hardly explored factor in play; **intersectoral agreement.** In times where time is of the essence, collaboration matters most to provide the most beneficial future for all.

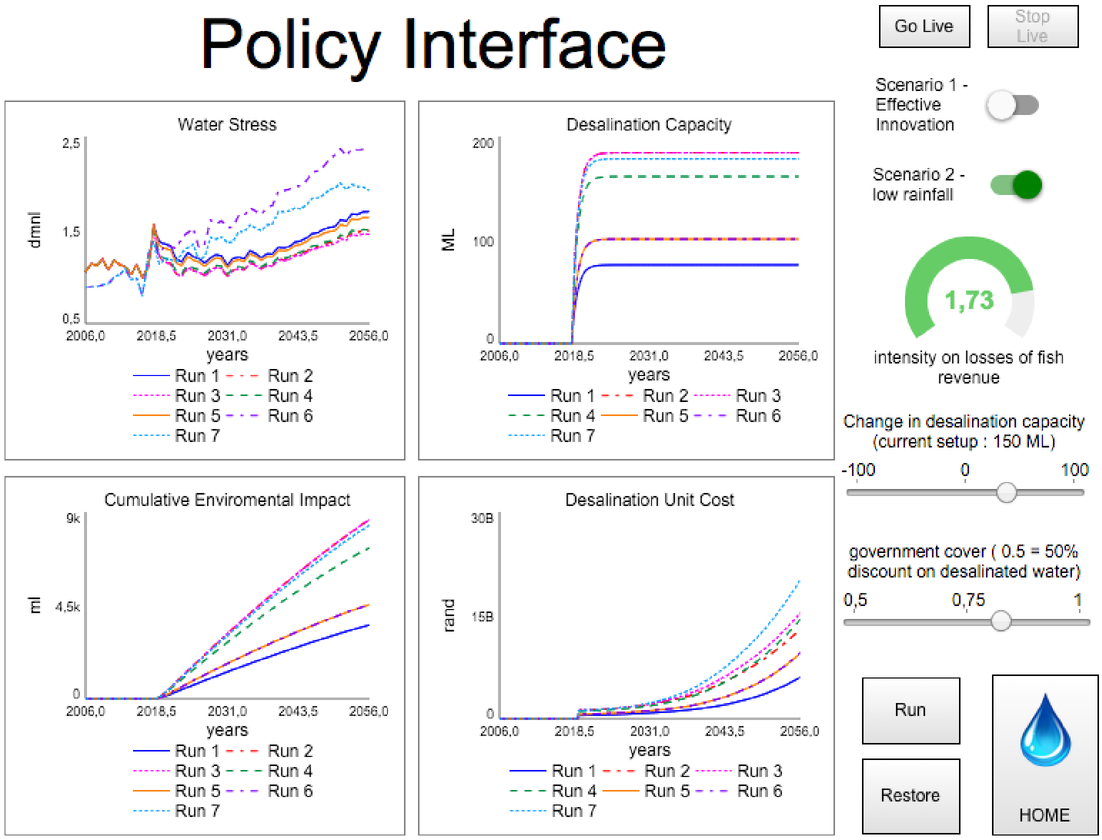
For further information,

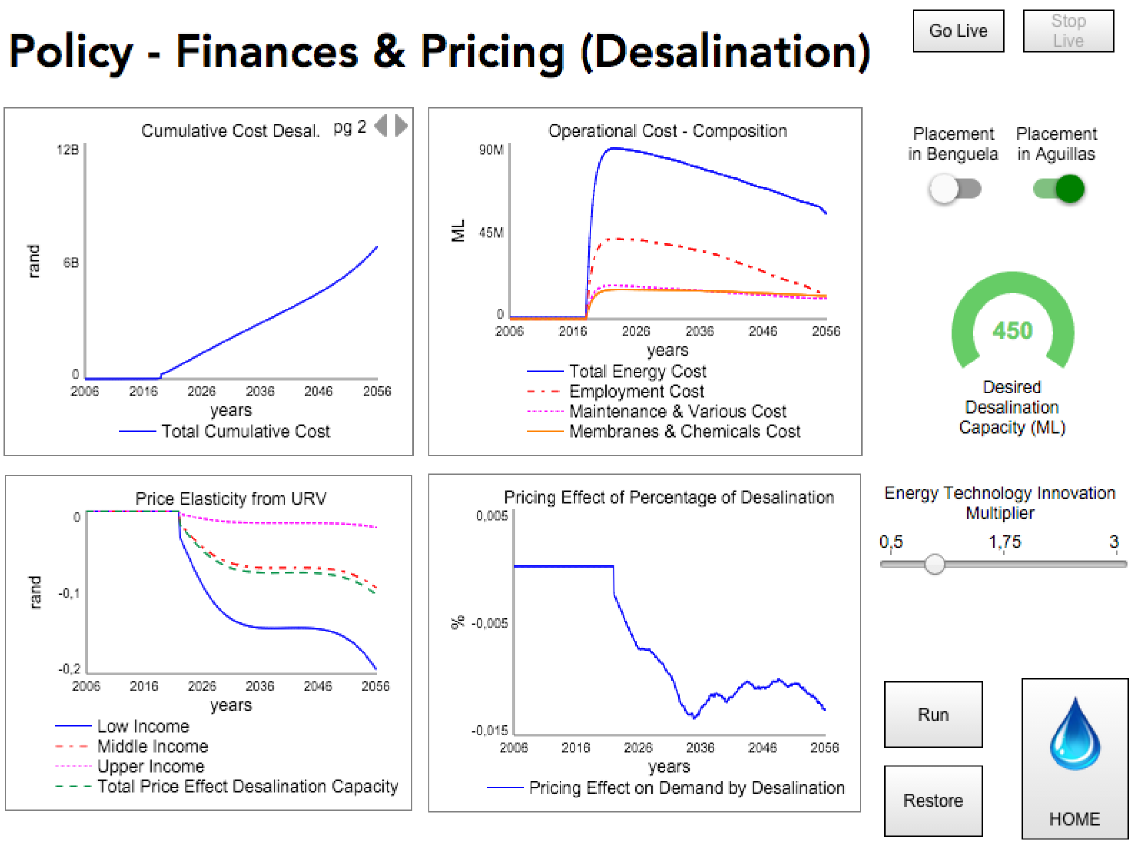
Please contact the lead modeler of *ACTdesal*, **Mr. Teun Sluijs** on **+27 160196263** or teun_sluijs@hotmail.com. Alternatively, please contact **Dr. Jai Clifford Holmes** on jai.clifford.holmes@gmail.com. To keep updated on the progress, please visit *www.ACTdesal.com*

Annex V. interface

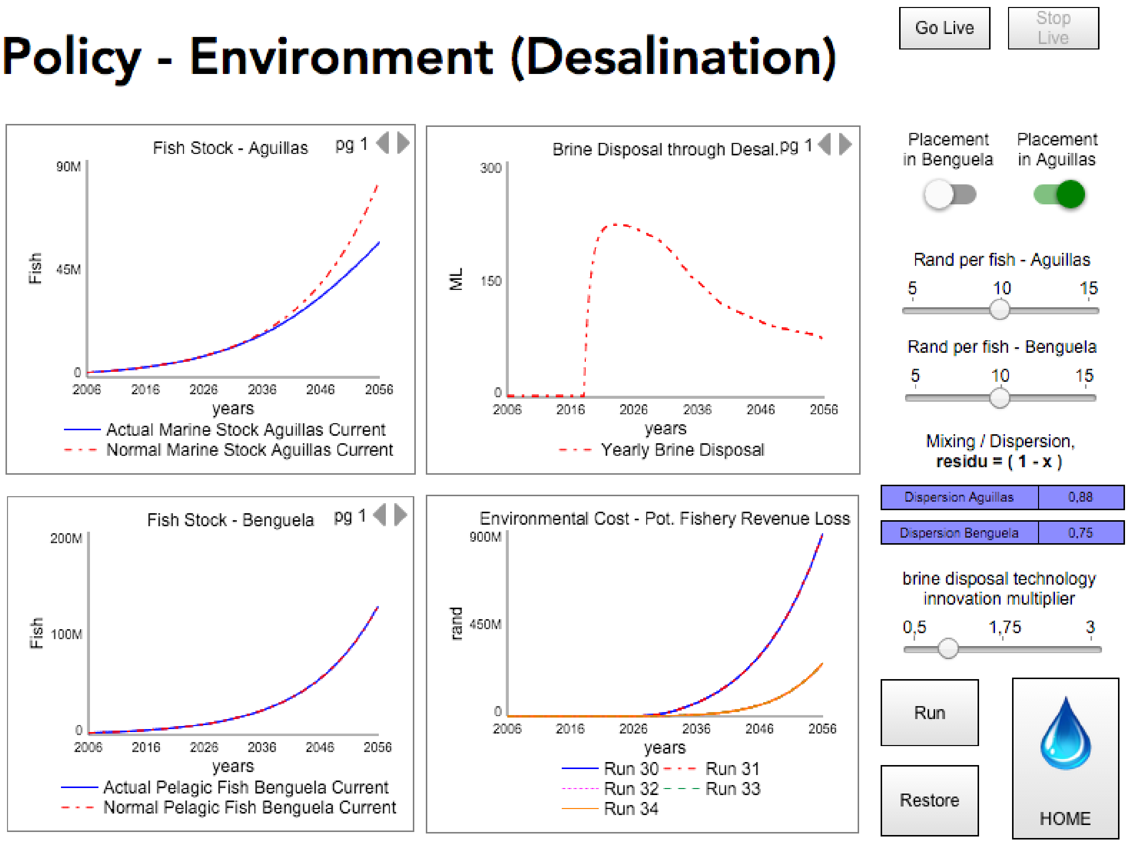

ACTdesal
A Systemic Exploration in Long-Term Viability on Desalination of Cape Town
Policy Interface
Finances & Pricing
Environment
Supply
Demand
Total Model
ABOUT
Teun Sluijs, MsC
Jai Clifford-Holmes, PhD


ABOUT
The Goal
The development of a model-based decision-support tool on the economic, technical and environmental impacts of long-term desalination in the Western Cape.
The Method
System Dynamics is a method of cause-effect interrelationships over time - it uses differential equations to capture and quantify behavior over time through the 'inside of the system'. The resulting model aims to portray the current interrelated state-of-the-art on desalination and the long-term development thereof.
Surface Water Supply
Demand & Supply
Ground Water
Water Re-use
Desalination
Water Demand
Environmental Impact Desalination
Desalination Capacity
Cost Desalination
Price Effects Desalination
The Aim
To create a holistic understanding on long-term desalination and to create a visual interface to be utilized by both technical and non- technical stakeholders.
The Collab
Collaborating mainly with researchers and UCT and Stellenbosch, aiming to gain input from other specialists, government officials, and other interested and affected stakeholders.
CLD
HOME

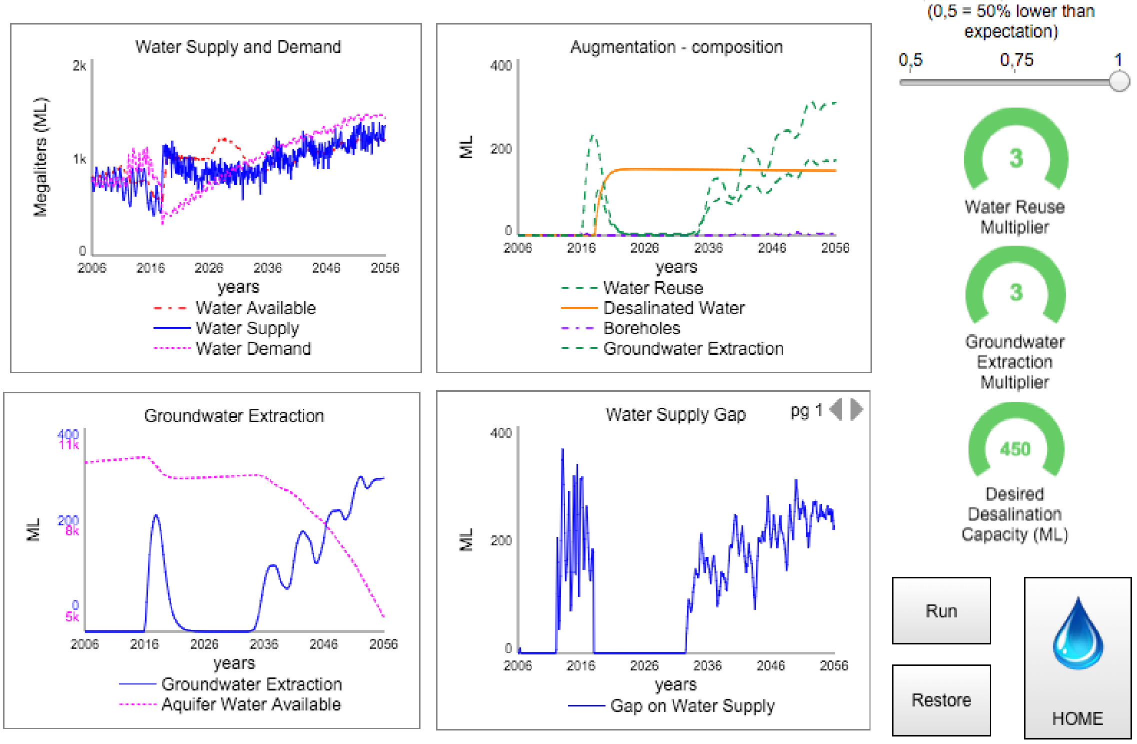

Policy Interface
Go Live
Stop Live
Water Stress
dmnl
years
Run 1 Run 2 Run 3 Run 4 Run 5 Run 6 Run 7
Desalination Capacity
ML
years
Run 1 Run 2 Run 3 Run 4 Run 5 Run 6 Run 7
Cumulative Enviromental Impact
ml
years
Run 1 Run 2 Run 3 Run 4 Run 5 Run 6 Run 7
Desalination Unit Cost
rand
years
Run 1 Run 2 Run 3 Run 4 Run 5 Run 6 Run 7
Scenario 1 - Effective Innovation
Scenario 2 - low rainfall
1,73
intensity on losses of fish revenue
Change in desalination capacity (current setup : 150 ML)
-100 0 100
government cover (0.5 = 50% discount on desalinated water)
0,5 0,75 1
Run
Restore
HOME


Policy - Finances & Pricing (Desalination)
Go Live
Stop Live
Cumulative Cost Desal.
pg 2
rand
years
Total Cumulative Cost
Operational Cost - Composition
ML
years
Total Energy Cost
Employment Cost
Maintenance & Various Cost
Membranes & Chemicals Cost
Placement in Benguela
Placement in Aguillas
450
Desired Desalination Capacity (ML)
Price Elasticity from URV
rand
years
Low Income
Middle Income
Upper Income
Total Price Effect Desalination Capacity
Pricing Effect of Percentage of Desalination
%
years
Pricing Effect on Demand by Desalination
Energy Technology Innovation Multiplier
0,5 1,75 3
Run
Restore
HOME

Policy - Environment (Desalination)

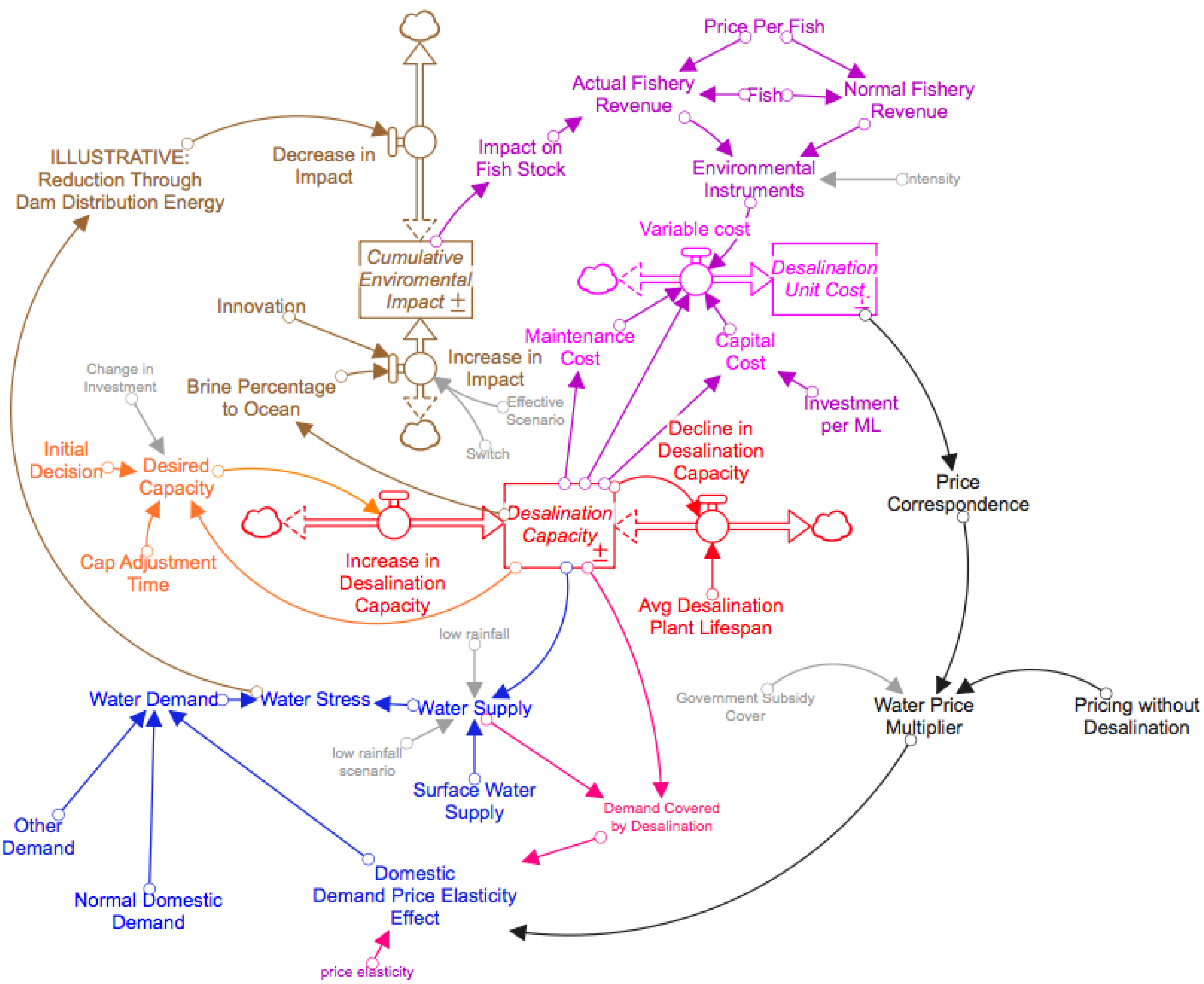


Policy - Demand & Supply

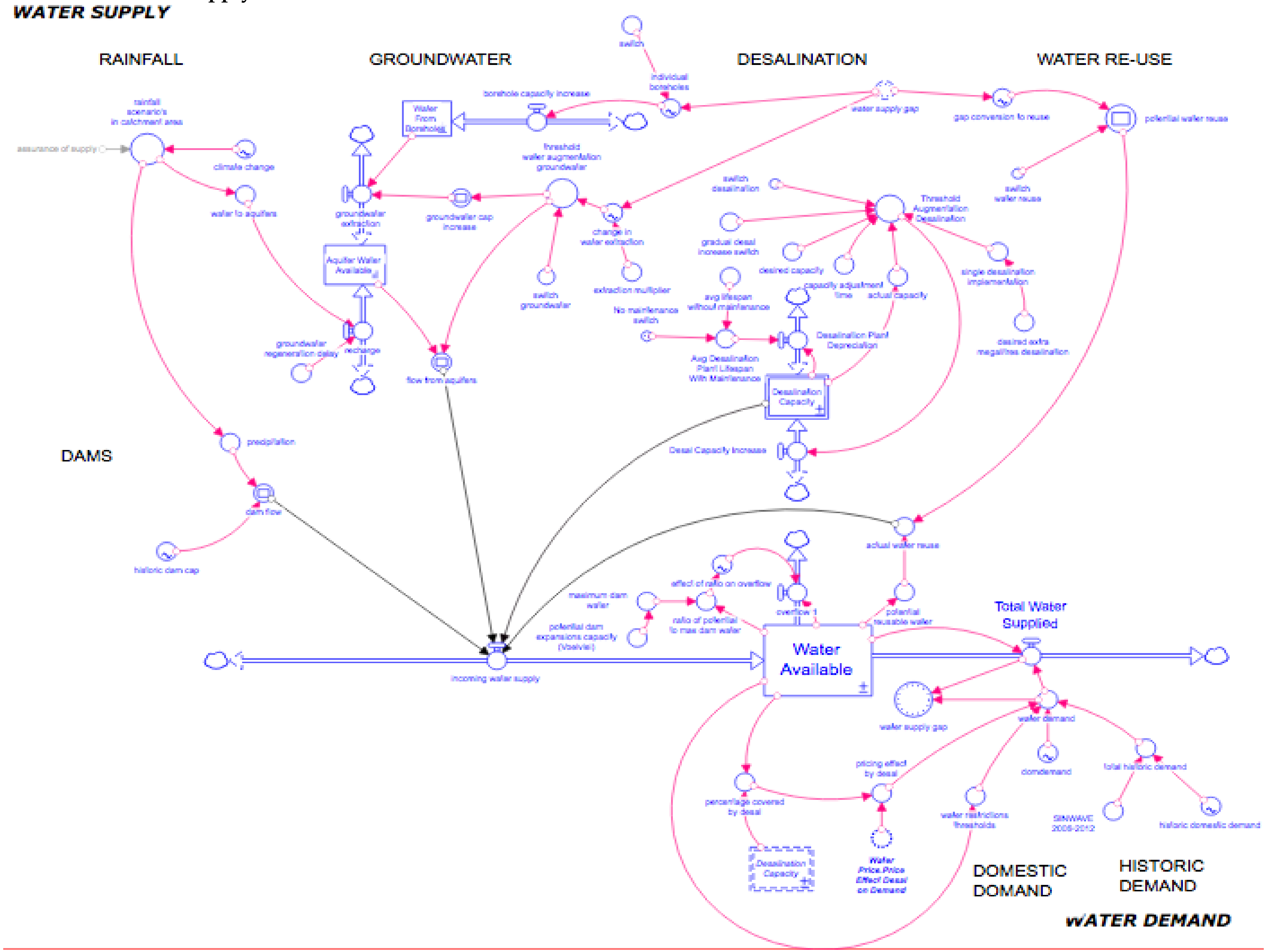


Annex VI. Model structures

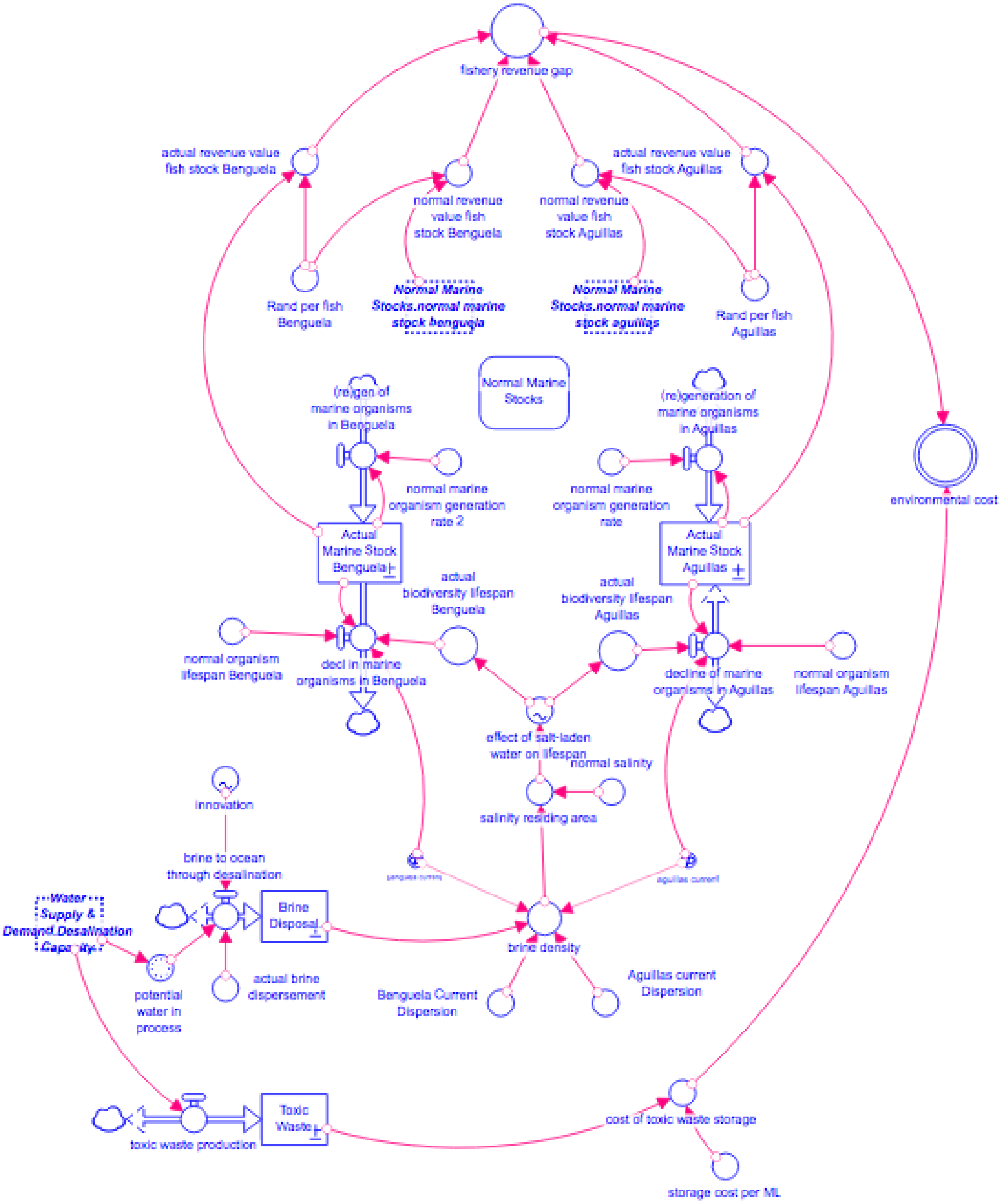
Structure 1. Concise overview model



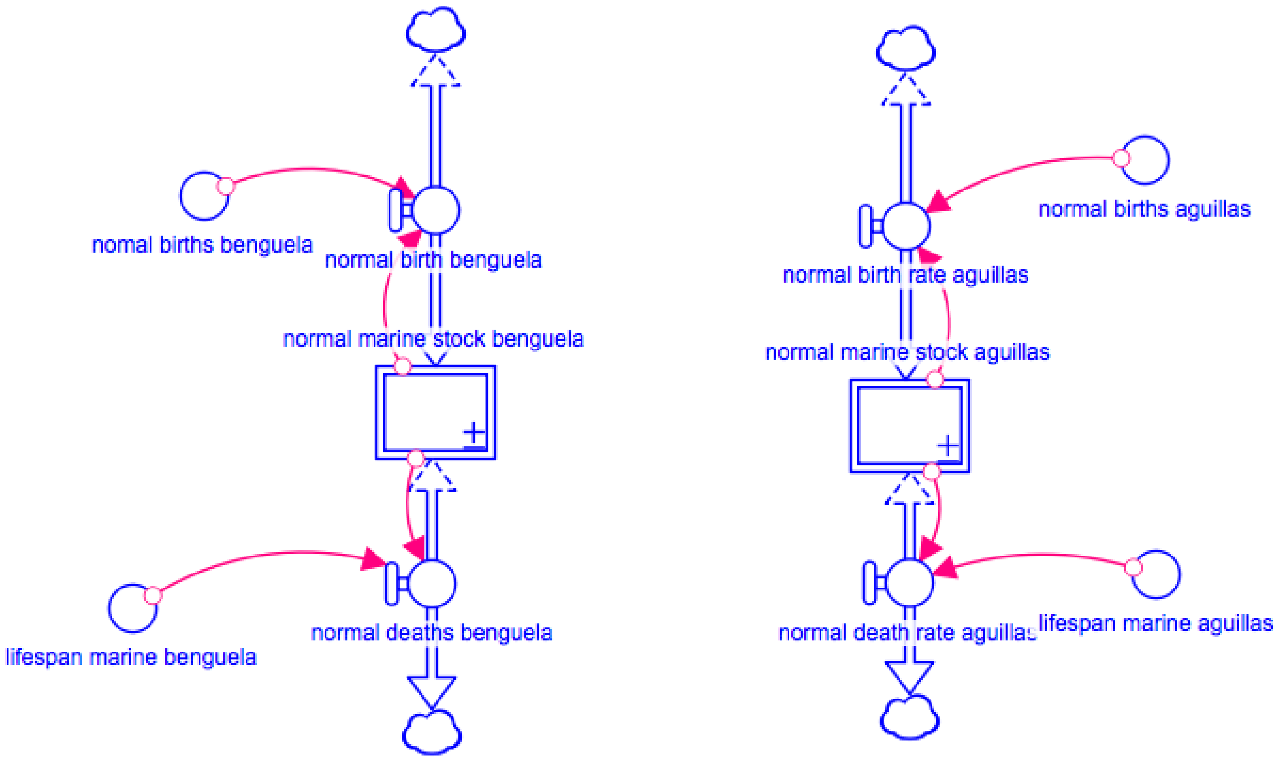
Structure 2: Water Supply and Demand



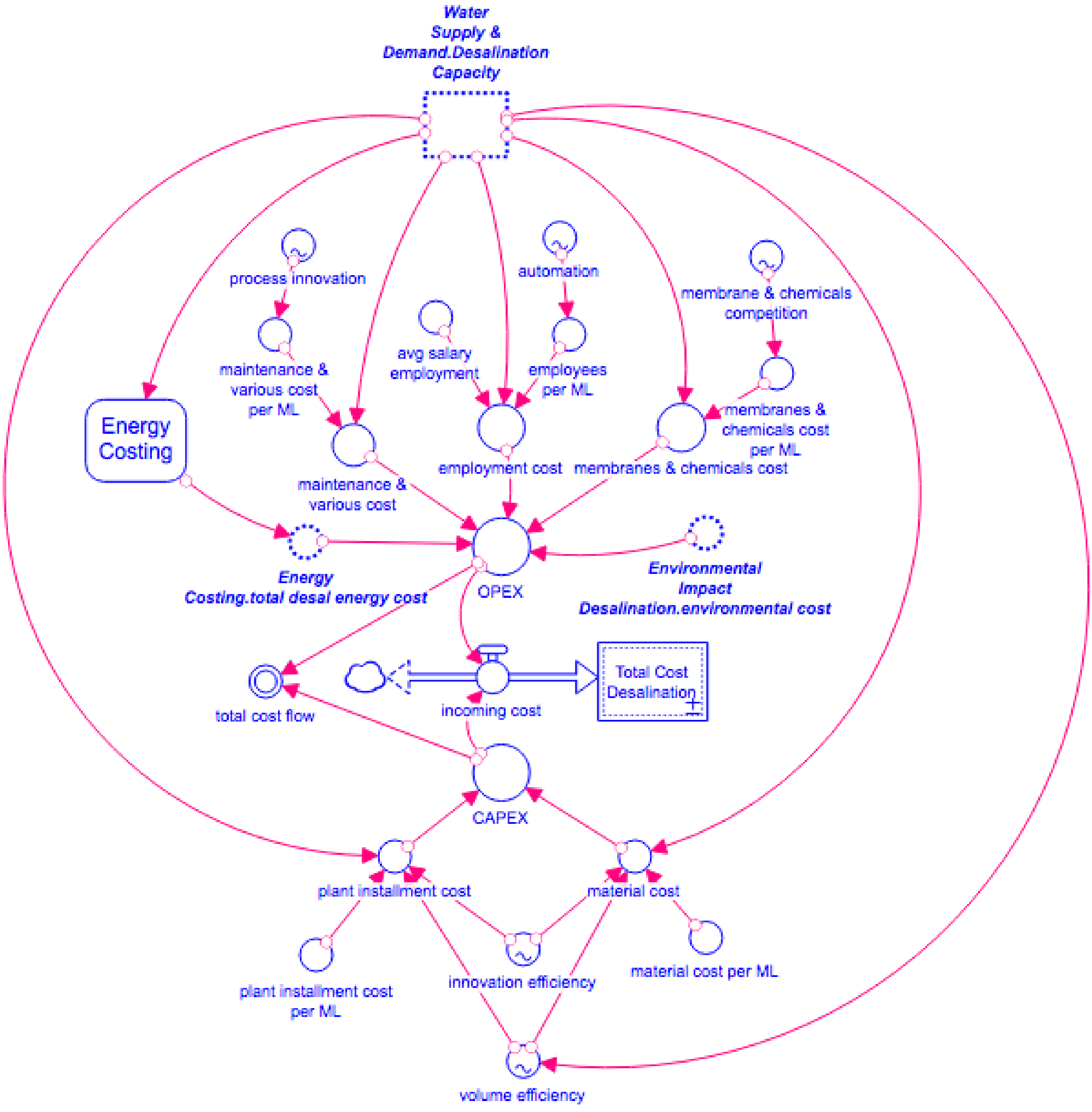
Structure 3: Environmental Cost



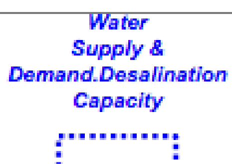
Structure 4: normal marine stocks



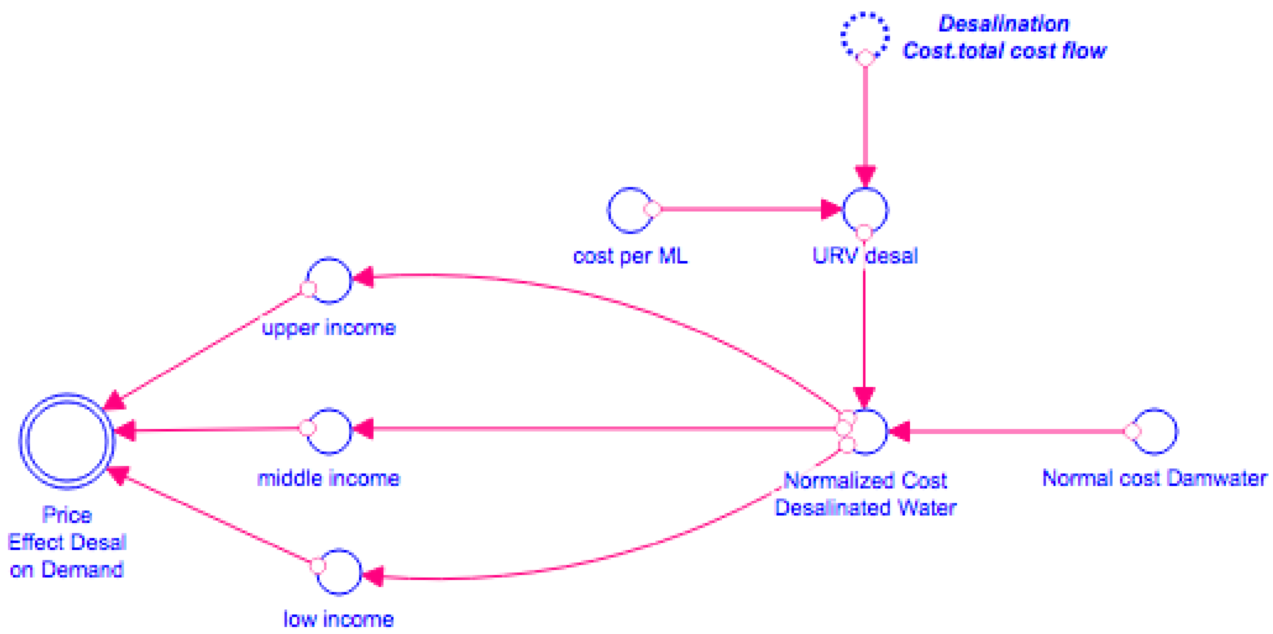
Structure 5: total desalinated cost



Structure 6: in-depth energy cost

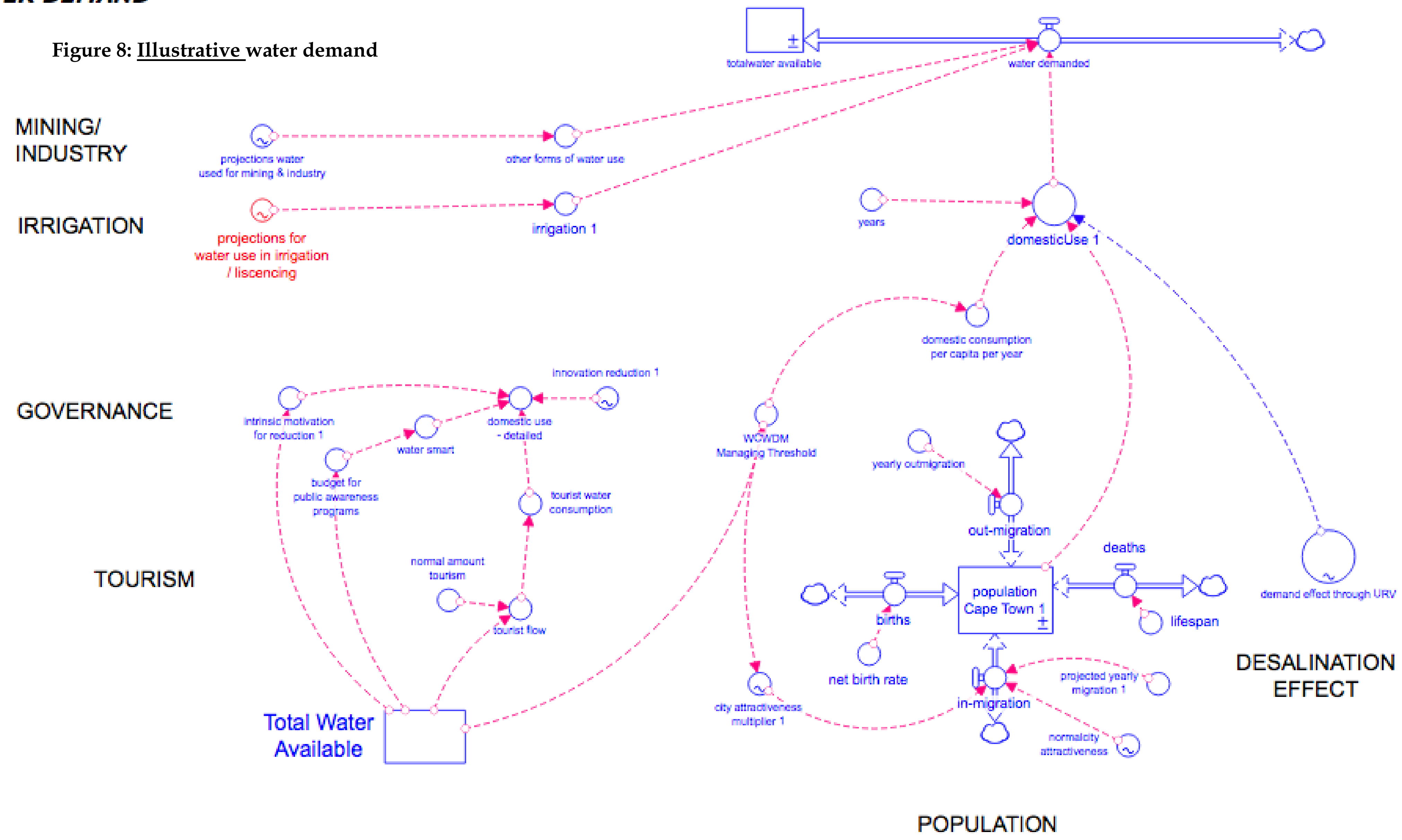


Structure 7: Price effect desalinated capacity


Desalination
Cost.total cost flow
cost per ML
URV desal
upper income
middle income
Normalized Cost
Desalinated Water
Normal cost Damwater
Price
Effect Desal
on Demand
low income

WATER DEMAND

Figure 8: Illustrative water demand



Annex VII. Model equations

Environmental_Impact_Desalination.energy_costs =
GRAPH("off-shore_distance")
(0, 3000), (100, 3080), (200, 3205), (300, 3330), (400, 3510), (500, 3700), (600, 3960), (700, 4220), (800, 4480), (900, 4740), (1000, 5000)
UNITS: dmnl
Environmental_Impact_Desalination.energy_requirement_per_ML = 3000000
UNITS: dmnl
Environmental_Impact_Desalination.innovation_energy_cost =
GRAPH(TIME)
(2006,00, 1,0000), (2007,00, 1,0000), (2008,00, 1,0000), (2009,00, 1,0000), (2010,00, 1,0000), (2011,00, 1,0000), (2012,00, 1,0000), (2013,00, 1,0000), (2014,00, 1,0000), (2015,00, 1,0000), (2016,00, 1,0000), (2017,00, 0,9966), (2018,00, 0,9966), (2019,00, 0,9931), (2020,00, 0,9829), (2021,00, 0,9726), (2022,00, 0,9623), (2023,00, 0,9520), (2024,00, 0,9417), (2025,00, 0,9143), (2026,00, 0,9040), (2027,00, 0,8920), (2028,00, 0,8766), (2029,00, 0,8560), (2030,00, 0,8354), (2031,00, 0,8217), (2032,00, 0,8080), (2033,00, 0,7943), (2034,00, 0,7806), (2035,00, 0,7686), (2036,00, 0,7566), (2037,00, 0,74285), (2038,00, 0,7189), (2039,00, 0,7017), (2040,00, 0,6880), (2041,00, 0,6777), (2042,00, 0,6606), (2043,00, 0,6571), (2044,00, 0,6366), (2045,00, 0,6263), (2046,00, 0,6229), (2047,00, 0,5989), (2048,00, 0,5783), (2049,00, 0,5680), (2050,00, 0,5509), (2051,00, 0,5371), (2052,00, 0,5234), (2053,00, 0,4994), (2054,00, 0,4857), (2055,00, 0,4720), (2056,00, 0,4274)
UNITS: dmnl
Environmental_Impact_Desalination."off-shore_distance" = slider
UNITS: dmnl
Environmental_Impact_Desalination.pickup_rate_by_aguillas =
GRAPH("off-shore_distance")
(0,8000, 130,9), (0,8200, 206,75), (0,8400, 282,6), (0,8600, 358,45), (0,8800, 434,3), (0,9000, 532,02), (0,9200, 629,74), (0,9400, 727,46), (0,9600, 825,18), (0,9800, 922,9), (1,0000, 1000,0)
UNITS: dmnl
Environmental_Impact_Desalination.pickup_rate_by_current_benguela
= GRAPH("off-shore_distance"*TIME)

(0,6000, 125,7), (0,6380, 182,3), (0,6760, 266,3), (0,7140, 350,3), (0,7520, 434,3), (0,7900, 518,3), (0,8280, 602,3), (0,8660, 686,3), (0,9040, 770,3), (0,9420, 854,3), (0,9800, 1000,0)

UNITS: dmnl

Environmental_Impact_Desalination.reduction_in_energy_requirement_pumping_costs_dam_water_distribution = ((150*energy_requirement_per_ML) *innovation_energy_cost)

UNITS: dmnl

Environmental_Impact_Desalination.revenue_value_direct_killrate_through_openwater_intake_per_ML = 1

UNITS: dmnl

Environmental_Impact_Desalination.slider = 900

UNITS: dmnl

Water_Supply_&_Demand.change_in_investment_water_reuse = 1

UNITS: dmnl/year

Water_Supply_&_Demand.sw_supp = GRAPH(TIME)

(2006,00, 1090), (2007,00, 1090), (2008,00, 1090), (2009,00, 1090), (2010,00, 1080), (2011,00, 1050), (2012,00, 1040), (2013,00, 1010), (2014,00, 990), (2015,00, 920), (2016,00, 870), (2017,00, 810), (2018,00, 760), (2019,00, 660), (2020,00, 380), (2021,00, 410), (2022,00, 760), (2023,00, 785), (2024,00, 810), (2025,00, 850), (2026,00, 890), (2027,00, 910), (2028,00, 930), (2029,00, 950), (2030,00, 1010), (2031,00, 1060), (2032,00, 1110), (2033,00, 1120), (2034,00, 1140), (2035,00, 1160), (2036,00, 1180), (2037,00, 1200), (2038,00, 1220), (2039,00, 1240), (2040,00, 1260), (2041,00, 1280), (2042,00, 1300), (2043,00, 1315), (2044,00, 1330), (2045,00, 1343,33333333), (2046,00, 1356,66666667), (2047,00, 1370), (2048,00, 1375), (2049,00, 1380), (2050,00, 1385), (2051,00, 1390), (2052,00, 1400), (2053,00, 1420), (2054,00, 1440), (2055,00, 1450), (2056,00, 1460)

UNITS: dmnl

Water_Supply_&_Demand.water_reuse_augmentation_goal = 0,25

UNITS: dmnl/year

****

small_overview_model_running:

****

Actual_Fishery_Revenue = (Fish*Price_Per_Fish)*Impact_on_Fish_Stock

UNITS: rand

Avg_Desalination_Plant_Lifespan = 20

UNITS: year

Brine_Percentage_to_Ocean = (2,5*Desalination_Capacity)*0,6

UNITS: ML

Cap_Adjustment_Time = 1

UNITS: years

Capital_Cost = PULSE(Investment_per_ML*Desalination_Capacity; 2019; 100)

UNITS: rand/year

Change_in_Investment = 0

UNITS: ML

Cumulative_Enviromental_Impact(t) = Cumulative_Enviromental_Impact(t - dt) + (Increase_in_Impact - Decrease_in_Impact) * dt

INIT Cumulative_Enviromental_Impact = 1

UNITS: ml

INFLOWS:

Increase_in_Impact = IF Switch =1 THEN Brine_Percentage_to_Ocean-((Innovation*Effective_Scenario)*Brine_Percentage_to_Ocean)

ELSE Brine_Percentage_to_Ocean-(Innovation*Brine_Percentage_to_Ocean)

UNITS: ml/year

OUTFLOWS:

Decrease_in_Impact

= ILLUSTRATIVE:_Reduction_Through_Dam_Distribution_Energy*0

UNITS: ml/year

Demand_Covered_by_Desalination = Desalination_Capacity/Water_Supply

UNITS: dmnl

Desalination_Capacity(t) = Desalination_Capacity(t - dt)

+ (Increase_in_Desalination_Capacity - Decline_in_Desalination_Capacity) * dt

INIT Desalination_Capacity = 0,0001

UNITS: ML

INFLOWS:

Increase_in_Desalination_Capacity = Desired_Capacity

UNITS: ML/year

OUTFLOWS:

Decline_in_Desalination_Capacity

= Desalination_Capacity/Avg_Desalination_Plant_Lifespan

UNITS: ML/year

Desalination_Unit_Cost(t) = Desalination_Unit_Cost(t - dt) + (Variable_cost) * dt

INIT Desalination_Unit_Cost = 1

UNITS: rand

INFLOWS:

Variable_cost=

Capital_Cost+(Maintenance_Cost*Desalination_Capacity)+Environmental_Instruments

UNITS: rand/year

Desired_Capacity = IF (TIME >2018)THEN ((Initial_Decision+Change_in_Investment)-Desalination_Capacity)/Cap_Adjustment_Time ELSE 0

UNITS: ml/year

Domestic_Demand_Price_Elasticity_Effect =

(Water_Price_Multiplier*price_elasticity)*Demand_Covered_by_Desalination

UNITS: rand/l3

Effective_Scenario = 1,2

UNITS: dmnl

Environmental_Instruments = (Normal_Fishery_Revenue-Actual_Fishery_Revenue)*intensity

UNITS: rand

Fish = GRAPH(TIME)

(2006,00, 600000), (2007,00, 600000), (2008,00, 600000), (2009,00, 600000), (2010,00, 600000), (2011,00, 600000), (2012,00, 600000), (2013,00, 600000), (2014,00, 600000), (2015,00, 600000), (2016,00, 600000), (2017,00, 600000), (2018,00, 700000), (2019,00, 1000000), (2020,00, 1200000), (2021,00, 1400000), (2022,00, 1500000), (2023,00, 1700000), (2024,00, 1900000), (2025,00, 2100000), (2026,00, 2300000), (2027,00, 2600000), (2028,00, 2700000), (2029,00, 3000000), (2030,00, 3200000), (2031,00, 3500000), (2032,00, 3700000), (2033,00, 3900000), (2034,00, 4100000), (2035,00, 4300000), (2036,00, 4400000), (2037,00, 5100000), (2038,00, 5600000), (2039,00, 5900000), (2040,00, 6400000), (2041,00, 6700000), (2042,00, 7200000), (2043,00, 7400000), (2044,00, 8000000), (2045,00, 8500000), (2046,00, 8800000), (2047,00, 9300000), (2048,00, 9700000), (2049,00, 10300000), (2050,00, 11100000), (2051,00, 12100000), (2052,00, 12600000), (2053,00, 13500000), (2054,00, 14200000), (2055,00, 15000000), (2056,00, 18000000)

UNITS: fish

Government_Subsidy_Cover = 0,1

UNITS: dmnl

ILLUSTRATIVE:_Reduction_Through_Dam_Distribution_Energy = Water_Stress

UNITS: dmnl

Impact_on_Fish_Stock = GRAPH(Cumulative_Enviromental_Impact)

(0, 0,9947), (600, 0,9605), (1200, 0,9184), (1800, 0,8737), (2400, 0,8132), (3000, 0,7447), (3600, 0,6895), (4200, 0,6289), (4800, 0,5763), (5400, 0,5342), (6000, 0,5000)

UNITS: dmnl

Initial_Decision = 150

UNITS: ML

Innovation = GRAPH(TIME)

(2018,00, 0,0100), (2018,76, 0,0111), (2019,52, 0,0122), (2020,28, 0,017775), (2021,04, 0,02335), (2021,80, 0,028925), (2022,56, 0,0345), (2023,32, 0,0403), (2024,08, 0,0461), (2024,84, 0,0519), (2025,60, 0,0577), (2026,36, 0,0635), (2027,12, 0,0692285714286), (2027,88, 0,0749571428571), (2028,64, 0,0806857142857), (2029,40, 0,0864142857143), (2030,16, 0,0921428571429), (2030,92, 0,0978714285714), (2031,68, 0,1036), (2032,44, 0,1100125), (2033,20, 0,116425), (2033,96, 0,1228375), (2034,72, 0,12925), (2035,48, 0,1356625), (2036,24, 0,142075), (2037,00, 0,1484875), (2037,76, 0,1549), (2038,52, 0,16130625), (2039,28, 0,1677125), (2040,04, 0,17411875), (2040,80, 0,180525), (2041,56, 0,18693125), (2042,32, 0,1933375), (2043,08, 0,19974375), (2043,84, 0,20615), (2044,60, 0,21255625), (2045,36, 0,2189625), (2046,12, 0,22536875), (2046,88, 0,231775), (2047,64, 0,23818125), (2048,40, 0,2445875), (2049,16, 0,25099375), (2049,92, 0,2574), (2050,68, 0,2685375), (2051,44, 0,279675), (2052,20, 0,2908125), (2052,96, 0,30195), (2053,72, 0,3130875), (2054,48, 0,324225), (2055,24, 0,3353625), (2056,00, 0,4000)

UNITS: dmnl/year

intensity = 1

UNITS: dmnl

Investment_per_ML = 10000000

UNITS: rand/ml

low_rainfall = 0

UNITS: dmnl

low_rainfall_scenario = GRAPH(TIME)

(2006,00, 1090), (2007,00, 1090), (2008,00, 1090), (2009,00, 1080), (2010,00, 1070), (2011,00, 1030), (2012,00, 980), (2013,00, 950), (2014,00, 940), (2015,00, 850), (2016,00, 780), (2017,00, 560), (2018,00, 530), (2019,00, 550), (2020,00, 510), (2021,00, 560), (2022,00, 570), (2023,00, 520), (2024,00, 570), (2025,00, 550), (2026,00, 650), (2027,00, 650), (2028,00, 550), (2029,00, 620), (2030,00, 620), (2031,00, 630), (2032,00, 650), (2033,00, 660), (2034,00, 670), (2035,00, 680), (2036,00, 700), (2037,00, 700), (2038,00, 700), (2039,00, 680), (2040,00, 680), (2041,00, 680), (2042,00, 690), (2043,00, 700), (2044,00, 710), (2045,00, 710), (2046,00, 700), (2047,00, 700), (2048,00, 700), (2049,00, 680), (2050,00, 670), (2051,00, 680), (2052,00, 700), (2053,00, 710), (2054,00, 710), (2055,00, 720), (2056,00, 730)

UNITS: dmnl

Maintenance_Cost = GRAPH(TIME*Desalination_Capacity)

(2022,00, 552000), (2022,68, 545000), (2023,36, 538000), (2024,04, 531000), (2024,72, 525000), (2025,40, 521000), (2026,08, 514000), (2026,76, 504000), (2027,44, 501000), (2028,12, 490000), (2028,80, 483000), (2029,48, 473000), (2030,16, 463000), (2030,84, 453000), (2031,52, 446000), (2032,20, 439000), (2032,88, 432000), (2033,56, 429000), (2034,24, 425000), (2034,92, 418000), (2035,60, 414500), (2036,28, 411000), (2036,96, 405000), (2037,64, 398000), (2038,32, 394000), (2039,00, 387000), (2039,68, 384000), (2040,36, 377000), (2041,04, 374000), (2041,72, 370000), (2042,40, 367000), (2043,08, 362000), (2043,76, 357000), (2044,44, 351000), (2045,12, 345000), (2045,80, 339000), (2046,48, 336000), (2047,16, 326000), (2047,84, 322000), (2048,52, 315000), (2049,20, 309000), (2049,88, 298000), (2050,56, 291000), (2051,24, 285000), (2051,92, 279500), (2052,60, 274000), (2053,28, 267000), (2053,96, 257000), (2054,64, 250000), (2055,32, 243000), (2056,00, 237000)

UNITS: rand/ml/year

Normal_Domestic_Demand = GRAPH(TIME)

(2006,00, 820), (2007,00, 820), (2008,00, 820), (2009,00, 830), (2010,00, 830), (2011,00, 860), (2012,00, 840), (2013,00, 860), (2014,00, 740), (2015,00, 660), (2016,00, 440), (2017,00, 510), (2018,00, 550), (2019,00, 570), (2020,00, 620), (2021,00, 680), (2022,00, 680), (2023,00, 690), (2024,00, 790), (2025,00, 790), (2026,00, 780), (2027,00, 810), (2028,00, 840), (2029,00, 920), (2030,00, 940), (2031,00, 900), (2032,00, 930), (2033,00, 1040), (2034,00, 1050), (2035,00, 1130), (2036,00, 1130), (2037,00, 1100), (2038,00, 1160), (2039,00, 1140), (2040,00, 1260), (2041,00, 1260), (2042,00, 1290), (2043,00, 1340), (2044,00, 1350), (2045,00, 1400), (2046,00, 1450), (2047,00, 1460), (2048,00, 1500), (2049,00, 1520), (2050,00, 1530), (2051,00, 1610), (2052,00, 1590), (2053,00, 1680), (2054,00, 1670), (2055,00, 1700), (2056,00, 1700)

UNITS: ml/year

Normal_Fishery_Revenue = Fish*Price_Per_Fish

UNITS: rand

Other_Demand = GRAPH(TIME)

(2006,00, 150,0), (2007,00, 152,882608696), (2008,00, 155,765217391), (2009,00, 158,647826087), (2010,00, 161,530434783), (2011,00, 164,413043478), (2012,00, 167,295652174), (2013,00, 170,17826087), (2014,00, 173,060869565), (2015,00, 175,943478261), (2016,00, 178,826086957), (2017,00, 181,708695652), (2018,00, 184,591304348), (2019,00, 187,473913043), (2020,00, 190,356521739), (2021,00, 193,239130435), (2022,00, 196,12173913), (2023,00, 199,004347826), (2024,00, 201,886956522), (2025,00, 204,769565217), (2026,00, 207,652173913), (2027,00, 210,534782609), (2028,00, 213,417391304), (2029,00, 216,3), (2030,00, 220,0), (2031,00, 223,7), (2032,00, 227,4), (2033,00, 231,1), (2034,00, 235,7), (2035,00, 240,3), (2036,00, 243,4), (2037,00, 246,5), (2038,00, 249,6), (2039,00, 252,7), (2040,00, 255,8), (2041,00, 258,9), (2042,00, 262,0), (2043,00, 266,2), (2044,00, 270,4), (2045,00, 274,6), (2046,00, 278,4), (2047,00, 282,2), (2048,00, 286,0), (2049,00, 289,8), (2050,00, 293,6), (2051,00, 297,4), (2052,00, 301,74), (2053,00, 306,08), (2054,00, 310,42), (2055,00, 314,76), (2056,00, 319,1)

UNITS: ml/year

Price_Correspondence = Desalination_Unit_Cost/5000000000

UNITS: rand

price_elasticity = 1,19

UNITS: dmnl

Price_Per_Fish = 100

UNITS: Rand/fish

Pricing_without_Desalination = 5

UNITS: rand/l3

Surface_Water_Supply = GRAPH(TIME)

(2006,00, 920), (2007,00, 850), (2008,00, 870), (2009,00, 830), (2010,00, 920), (2011,00, 870), (2012,00, 890), (2013,00, 930), (2014,00, 890), (2015,00, 740), (2016,00, 630), (2017,00, 630), (2018,00, 470), (2019,00, 500), (2020,00, 530), (2021,00, 580), (2022,00, 660), (2023,00, 690), (2024,00, 710), (2025,00, 740), (2026,00, 750), (2027,00, 810), (2028,00, 800), (2029,00, 840), (2030,00, 870), (2031,00, 920), (2032,00, 890), (2033,00, 970), (2034,00, 1000), (2035,00, 990), (2036,00, 1020), (2037,00, 1040), (2038,00, 1050), (2039,00, 1040), (2040,00, 1070), (2041,00, 1080), (2042,00, 1090), (2043,00, 1090), (2044,00, 1090), (2045,00, 1100), (2046,00, 1100), (2047,00, 1100), (2048,00, 1100), (2049,00, 1100), (2050,00, 1100), (2051,00, 1100), (2052,00, 1100), (2053,00, 1100), (2054,00, 1100), (2055,00, 1100), (2056,00, 1100)

UNITS: ml/year

Switch = 0

UNITS: dmnl

Water_Demand = (Normal_Domestic_Demand-(Normal_Domestic_Demand*Domestic_Demand_Price_Elasticity_Effect))+Other_Demand

UNITS: ml/year

Water_Price_Multiplier = (Price_Correspondence*Government_Subsidy_Cover)/Pricing_without_Desalination

UNITS: rand/l3

Water_Stress = Water_Demand/Water_Supply

UNITS: dmnl

Water_Supply = IF low_rainfall=1 THEN (low_rainfall_scenario + Desalination_Capacity)ELSE (Surface_Water_Supply+Desalination_Capacity)

UNITS: ml/year

****

Desalination_Cost.variable_cost:

****

Desalination_Cost.automation = GRAPH(TIME)

(2006,00, 0,9960), (2007,00, 0,9960), (2008,00, 0,9960), (2009,00, 0,9960), (2010,00, 0,9960), (2011,00, 0,9960), (2012,00, 0,9960), (2013,00, 0,9960), (2014,00, 0,9960), (2015,00, 0,9960), (2016,00, 0,9960), (2017,00, 0,9920), (2018,00, 0,9920), (2019,00, 0,9920), (2020,00, 0,9880), (2021,00, 0,9880), (2022,00, 0,9800), (2023,00, 0,9720), (2024,00, 0,9640), (2025,00, 0,9640), (2026,00, 0,9600), (2027,00, 0,9520), (2028,00, 0,9440), (2029,00, 0,9280), (2030,00, 0,9200), (2031,00, 0,9080), (2032,00, 0,8960), (2033,00, 0,8880), (2034,00, 0,8680), (2035,00, 0,8480), (2036,00, 0,8320), (2037,00, 0,8200), (2038,00, 0,8000), (2039,00, 0,7840), (2040,00, 0,7520), (2041,00, 0,7320), (2042,00, 0,6960), (2043,00, 0,6720), (2044,00, 0,6440), (2045,00, 0,6200), (2046,00, 0,5880), (2047,00, 0,5520), (2048,00, 0,5240), (2049,00, 0,5000), (2050,00, 0,4720), (2051,00, 0,4480), (2052,00, 0,4320), (2053,00, 0,4000), (2054,00, 0,3600), (2055,00, 0,3280), (2056,00, 0,3000)

UNITS: people/year

Desalination_Cost.avg_salary_employment = 140000

UNITS: rand/people

Desalination_Cost.CAPEX = material_cost+plant_installment_cost

UNITS: rand/year

Desalination_Cost.employees_per_ML = 2*automation

UNITS: people/year

Desalination_Cost.employment_cost = Water_Supply_&_Demand.Desalination_Capacity*(avg_salary_employment*employees_per_ML)

UNITS: rand/ml/year

Desalination_Cost.innovation_efficiency = GRAPH(TIME)

(2006,00, 1,0000), (2007,00, 1,0000), (2008,00, 1,0000), (2009,00, 1,0000), (2010,00, 1,0000), (2011,00, 1,0000), (2012,00, 1,0000), (2013,00, 1,0000), (2014,00, 1,0000), (2015,00, 1,0000), (2016,00, 1,0000), (2017,00, 1,0000), (2018,00, 1,0000), (2019,00, 1,0000), (2020,00, 1,0000), (2021,00, 1,0000), (2022,00, 0,9954), (2023,00, 0,9931), (2024,00, 0,9886), (2025,00, 0,9863), (2026,00, 0,9829), (2027,00, 0,9783), (2028,00, 0,9703), (2029,00, 0,9646), (2030,00, 0,9600), (2031,00, 0,9554), (2032,00, 0,9497), (2033,00, 0,9429), (2034,00, 0,9360), (2035,00, 0,9280), (2036,00, 0,9257), (2037,00, 0,9166), (2038,00, 0,9063), (2039,00, 0,9006), (2040,00, 0,8914), (2041,00, 0,8846), (2042,00, 0,8754), (2043,00, 0,8697), (2044,00, 0,8629), (2045,00, 0,8571), (2046,00, 0,8514), (2047,00, 0,8457), (2048,00, 0,8377), (2049,00, 0,8320), (2050,00, 0,8263), (2051,00, 0,8206), (2052,00, 0,8149), (2053,00, 0,8091), (2054,00, 0,8046), (2055,00, 0,8000), (2056,00, 0,8000)

UNITS: dmnl

Desalination_Cost.maintenance_&_various_cost = Water_Supply_&_Demand.Desalination_Capacity*maintenance_&_various_cost_per_ML

UNITS: rand/year

Desalination_Cost.maintenance_&_various_cost_per_ML = 120000*process_innovation

UNITS: rand/ml/year

Desalination_Cost.material_cost = (PULSE(Water_Supply_&_Demand.Desalination_Capacity*material_cost_per_ML; 2019; 200)*innovation_efficiency*volume_efficiency)

UNITS: rand/year

Desalination_Cost.material_cost_per_ML = 750000

UNITS: rand/ml

Desalination_Cost.membrane_&_chemicals_competition = GRAPH(TIME)
(2006,00, 1,0000), (2007,00, 1,0000), (2008,00, 1,0000), (2009,00, 1,0000), (2010,00, 1,0000), (2011,00, 1,0000), (2012,00, 1,0000), (2013,00, 1,0000), (2014,00, 1,0000), (2015,00, 1,0000), (2016,00, 1,0000), (2017,00, 1,0000), (2018,00, 1,0000), (2019,00, 1,0000), (2020,00, 1,0000), (2021,00, 1,0000), (2022,00, 1,0000), (2023,00, 1,0000), (2024,00, 0,9979), (2025,00, 0,9958), (2026,00, 0,9926), (2027,00, 0,9916), (2028,00, 0,9895), (2029,00, 0,9874), (2030,00, 0,9832), (2031,00, 0,9811), (2032,00, 0,9779), (2033,00, 0,9737), (2034,00, 0,9695), (2035,00, 0,9663), (2036,00, 0,9600), (2037,00, 0,9537), (2038,00, 0,9526), (2039,00, 0,9442), (2040,00, 0,9400), (2041,00, 0,9347), (2042,00, 0,9221), (2043,00, 0,9158), (2044,00, 0,9053), (2045,00, 0,8979), (2046,00, 0,8863), (2047,00, 0,8800), (2048,00, 0,8716), (2049,00, 0,8653), (2050,00, 0,8558), (2051,00, 0,8463), (2052,00, 0,8389), (2053,00, 0,8263), (2054,00, 0,8232), (2055,00, 0,8105), (2056,00, 0,8042)

UNITS: rand/year

Desalination_Cost.membranes_&_chemicals_cost =

Water_Supply_&_Demand.Desalination_Capacity*membranes_&_chemicals_cost_per_ML

UNITS: rand/year

Desalination_Cost.membranes_&_chemicals_cost_per_ML =

100000*membrane_&_chemicals_competition

UNITS: rand/ml/year

Desalination_Cost.OPEX =

+maintenance_&_various_cost+employment_cost+membranes_&_chemicals_cost+Energy_Costing.total_desal_energy_cost+Environmental_Impact_Desalination.environmental_cost

UNITS: rand/year

Desalination_Cost.plant_installment_cost =

(PULSE(Water_Supply_&_Demand.Desalination_Capacity*plant_installment_cost_per_ML ; 2019 ; 100) *innovation_efficiency*volume_efficiency)

UNITS: rand/year

Desalination_Cost.plant_installment_cost_per_ML = 1000000

UNITS: rand/ml

Desalination_Cost.process_innovation = GRAPH(TIME)

(2006,00, 1,0000), (2007,00, 1,0000), (2008,00, 1,0000), (2009,00, 1,0000), (2010,00, 1,0000), (2011,00, 1,0000), (2012,00, 1,0000), (2013,00, 1,0000), (2014,00, 1,0000), (2015,00, 1,0000), (2016,00, 1,0000), (2017,00, 1,0000), (2018,00, 1,0000), (2019,00, 0,9974), (2020,00, 0,9842), (2021,00, 0,9750), (2022,00, 0,9658), (2023,00, 0,95395), (2024,00, 0,9421), (2025,00, 0,93025), (2026,00, 0,9184), (2027,00, 0,9075), (2028,00, 0,8966), (2029,00, 0,8857), (2030,00, 0,8748), (2031,00, 0,8639), (2032,00, 0,8530), (2033,00, 0,8421), (2034,00, 0,830828571429), (2035,00, 0,819557142857), (2036,00, 0,808285714286), (2037,00, 0,797014285714), (2038,00, 0,785742857143), (2039,00, 0,774471428571), (2040,00, 0,7632), (2041,00, 0,749166666667), (2042,00, 0,735133333333), (2043,00, 0,7211), (2044,00, 0,711875), (2045,00, 0,70265), (2046,00, 0,693425), (2047,00, 0,6842), (2048,00, 0,670166666667), (2049,00, 0,656133333333), (2050,00, 0,6421), (2051,00, 0,6307), (2052,00, 0,6193), (2053,00, 0,6079), (2054,00, 0,6000), (2055,00, 0,6000), (2056,00, 0,6000)

UNITS: rand/year

Desalination_Cost.Total_Cost_Desalination(t) = Total_Cost_Desalination(t - dt) + (incoming_cost) * dt

INIT Desalination_Cost.Total_Cost_Desalination = 0

UNITS: rand

INFLOWS:

Desalination_Cost.incoming_cost = OPEX+CAPEX

UNITS: rand/year

Desalination_Cost.total_cost_flow = OPEX+CAPEX

UNITS: rand

Desalination_Cost.volume_efficiency = GRAPH(Water_Supply_&_Demand.Desalination_Capacity)

(100,0, 0,9886), (120,0, 0,9680), (140,0, 0,9177), (160,0, 0,8674), (180,0, 0,8263), (200,0, 0,7874), (220,0, 0,7463), (240,0, 0,7097), (260,0, 0,6686), (280,0, 0,6389), (300,0, 0,6183)

UNITS: dmnl/ml

****

Energy_Costing.Sector_1:

****

Energy_Costing.cost_per_celsius_per_ml = 30000

UNITS: rand/ML

Energy_Costing.energy_cost_per_ml = 100000

UNITS: rand/ML

Energy_Costing."energy_cost_pre-treatment" = potential_water_in_process_1*energycost_per_ML

UNITS: rand

Energy_Costing.energy_cost_water_pumping = water_recovery_factor*energy_cost_per_ml

UNITS: rand

Energy_Costing.energy_innovation_1 = GRAPH(TIME)

(2006,00, 1,0000), (2007,00, 1,0000), (2008,00, 1,0000), (2009,00, 1,0000), (2010,00, 1,0000), (2011,00, 1,0000), (2012,00, 1,0000), (2013,00, 1,0000), (2014,00, 1,0000), (2015,00, 1,0000), (2016,00, 1,0000), (2017,00, 1,0000), (2018,00, 1,0000), (2019,00, 0,9943), (2020,00, 0,9829), (2021,00, 0,9800), (2022,00, 0,9629), (2023,00, 0,9457), (2024,00, 0,9229), (2025,00, 0,9086), (2026,00, 0,8943), (2027,00, 0,8743), (2028,00, 0,8600), (2029,00, 0,8429), (2030,00, 0,8257), (2031,00, 0,8086), (2032,00, 0,8000), (2033,00, 0,7857), (2034,00, 0,7800), (2035,00, 0,7686), (2036,00, 0,7600), (2037,00, 0,7514), (2038,00, 0,7429), (2039,00, 0,7371), (2040,00, 0,7286), (2041,00, 0,7257), (2042,00, 0,7171), (2043,00, 0,7114), (2044,00, 0,7086), (2045,00, 0,7086), (2046,00, 0,7057), (2047,00, 0,7000), (2048,00, 0,6943), (2049,00, 0,6914), (2050,00, 0,6857), (2051,00, 0,6829), (2052,00, 0,6800), (2053,00, 0,6743), (2054,00, 0,6743), (2055,00, 0,6714), (2056,00, 0,6571)

UNITS: dmnl

Energy_Costing.energycost_per_ML = 200000

UNITS: rand/ml

Energy_Costing.fraction_of_day_plant_at_full_cap = 0,95

UNITS: dmnl

Energy_Costing.hourly_feed_flow_rate = 0,4

UNITS: dmnl

Energy_Costing.hourly_prod_rate = potential_water_in_process_1/24*fraction_of_day_plant_at_full_cap

UNITS: ML

Energy_Costing.potential_water_in_process_1 = Water_Supply_&_Demand.Desalination_Capacity*2,5

UNITS: ml

Energy_Costing.projected_temperature_increase_per_ml = GRAPH(TIME)
(2006,00, 1,0000), (2007,00, 1,0000), (2008,00, 1,0000), (2009,00, 1,0000), (2010,00, 1,0000), (2011,00, 1,0000), (2012,00, 1,0000), (2013,00, 1,0000), (2014,00, 1,0000), (2015,00, 1,0000), (2016,00, 1,0000), (2017,00, 1,0000), (2018,00, 1,0000), (2019,00, 1,0011), (2020,00, 1,0034), (2021,00, 1,0069), (2022,00, 1,0091), (2023,00, 1,0114), (2024,00, 1,0126), (2025,00, 1,0137), (2026,00, 1,0171), (2027,00, 1,0183), (2028,00, 1,0206), (2029,00, 1,0240), (2030,00, 1,0263), (2031,00, 1,0309), (2032,00, 1,0331), (2033,00, 1,0366), (2034,00, 1,0389), (2035,00, 1,0411), (2036,00, 1,0434), (2037,00, 1,0469), (2038,00, 1,0491), (2039,00, 1,0537), (2040,00, 1,0571), (2041,00, 1,0617), (2042,00, 1,0674), (2043,00, 1,0709), (2044,00, 1,0766), (2045,00, 1,0846), (2046,00, 1,0903), (2047,00, 1,1029), (2048,00, 1,1103), (2049,00, 1,1234), (2050,00, 1,1291), (2051,00, 1,1394), (2052,00, 1,1440), (2053,00, 1,1520), (2054,00, 1,1566), (2055,00, 1,1623), (2056,00, 1,2000)

UNITS: dmnl

Energy_Costing.total_desal_energy_cost =

(energy_cost_water_pumping+"energy_cost_pre-

treatment"+treatment_cost_per_celcius)*energy_innovation_1

UNITS: rand

Energy_Costing.treatment_cost_per_celcius =

(potential_water_in_process_1*cost_per_celsius_per_ml)*projected_temperatur

e_increase_per_ml

UNITS: rand

Energy_Costing.water_recovery_factor =

hourly_prod_rate/hourly_feed_flow_rate

UNITS: ML

****

Environmental_Impact_Desalination.environmental_impact:

****

Environmental_Impact_Desalination.actual_biodiversity_lifespan_Aguillas =

18*"effect_of_salt-laden_water_on_lifespan"

UNITS: dmnl

Environmental_Impact_Desalination.actual_biodiversity_lifespan_Benguela =

15*"effect_of_salt-laden_water_on_lifespan"

UNITS: dmnl

Environmental_Impact_Desalination.actual_brine_dispersement = 0,60

UNITS: ML/year

Environmental_Impact_Desalination.Actual_Marine_Stock_Aguillas(t) =

Actual_Marine_Stock_Aguillas(t - dt) +

("(re)generation_of_marine_organisms_in_Aguillas" -

decline_of_marine_organisms_in_Aguillas) * dt

INIT Environmental_Impact_Desalination.Actual_Marine_Stock_Aguillas =

1000000

UNITS: fish

INFLOWS:

Environmental_Impact_Desalination."(re)generation_of_marine_organisms_in

_Aguillas" =
Actual_Marine_Stock_Aguillas*normal_marine_organism_generation_rate
UNITS: fish/year
OUTFLOWS:

Environmental_Impact_Desalination.decline_of_marine_organisms_in_Aguillas = IF aguillas_current =1 THEN (Actual_Marine_Stock_Aguillas/actual_biodiversity_lifespan_Aguillas) ELSE Actual_Marine_Stock_Aguillas/normal_organism_lifespan_Aguillas
UNITS: fish/year
Environmental_Impact_Desalination.Actual_Marine_Stock_Benguela(t) = Actual_Marine_Stock_Benguela(t - dt) + ("(re)gen_of_marine_organisms_in_Benguela" - decl_in_marine_organisms_in_Benguela) * dt
INIT Environmental_Impact_Desalination.Actual_Marine_Stock_Benguela = 2000000
UNITS: fish
INFLOWS:

Environmental_Impact_Desalination."(re)gen_of_marine_organisms_in_Benguela" =
Actual_Marine_Stock_Benguela*normal_marine_organism_generation_rate_2
UNITS: fish/year
OUTFLOWS:

Environmental_Impact_Desalination.decl_in_marine_organisms_in_Benguela = IF benguela_current= 1 THEN (Actual_Marine_Stock_Benguela/actual_biodiversity_lifespan_Benguela) ELSE (Actual_Marine_Stock_Benguela/normal_organism_lifespan_Benguela)
UNITS: fish/year
Environmental_Impact_Desalination.actual_revenue_value_fish_stock_Aguillas = Actual_Marine_Stock_Aguillas*Rand_per_fish_Aguillas
UNITS: rand
Environmental_Impact_Desalination.actual_revenue_value_fish_stock_Bengue

la = Actual_Marine_Stock_Benguela*Rand_per_fish_Benguela
UNITS: rand
Environmental_Impact_Desalination.aguillas_current = 1
UNITS: dmnl
Environmental_Impact_Desalination.Aguillas_current_Dispersion = 0,88
UNITS: dmnl
Environmental_Impact_Desalination.benguela_current = 0
UNITS: dmnl
Environmental_Impact_Desalination.Benguela_Current_Dispersion = 0,75
UNITS: dmnl
Environmental_Impact_Desalination.brine_density = IF (benguela_current = 1) THEN Brine_Disposal*(1-Benguela_Current_Dispersion) ELSE (IF (aguillas_current=1) THEN Brine_Disposal*(1-Aguillas_current_Dispersion) ELSE 0)
UNITS: ML/dmnl
Environmental_Impact_Desalination.Brine_Disposal(t) = Brine_Disposal(t - dt) + (brine_to_ocean_through_desalination) * dt
INIT Environmental_Impact_Desalination.Brine_Disposal = 0
UNITS: ML
INFLOWS:

Environmental_Impact_Desalination.brine_to_ocean_through_desalination = (potential_water_in_process*actual_brine_dispersement) *innovation
UNITS: ML/year
Environmental_Impact_Desalination.cost_of_toxic_waste_storage = Toxic_Waste*storage_cost_per_ML
UNITS: rand
Environmental_Impact_Desalination."effect_of_salt-laden_water_on_lifespan" = GRAPH(salinity_residing_area)
(1,000, 0,9954), (1,200, 0,9909), (1,400, 0,9863), (1,600, 0,9680), (1,800, 0,9474), (2,000, 0,9177), (2,200, 0,8789), (2,400, 0,8171), (2,600, 0,7211), (2,800, 0,6480), (3,000, 0,6000)
UNITS: dmnl
Environmental_Impact_Desalination.environmental_cost =

fishery_revenue_gap+cost_of_toxic_waste_storage

UNITS: rand/year

Environmental_Impact_Desalination.fishery_revenue_gap = IF (TIME >2017) THEN (normal_revenue_value_fish_stock_Benguela-actual_revenue_value_fish_stock_Benguela) + (normal_revenue_value_fish_stock_Aguillas-actual_revenue_value_fish_stock_Aguillas) ELSE 0

UNITS: rand/ml

Environmental_Impact_Desalination.innovation = GRAPH(TIME)

(2018,00, 1,0000), (2018,76, 1,0000), (2019,52, 0,9966), (2020,28, 0,9931), (2021,04, 0,9863), (2021,80, 0,9829), (2022,56, 0,9794), (2023,32, 0,9726), (2024,08, 0,9657), (2024,84, 0,9589), (2025,60, 0,9486), (2026,36, 0,9314), (2027,12, 0,9040), (2027,88, 0,8903), (2028,64, 0,8697), (2029,40, 0,8560), (2030,16, 0,8320), (2030,92, 0,8080), (2031,68, 0,7840), (2032,44, 0,7669), (2033,20, 0,7531), (2033,96, 0,7086), (2034,72, 0,6949), (2035,48, 0,6709), (2036,24, 0,6537), (2037,00, 0,6297), (2037,76, 0,6057), (2038,52, 0,5817), (2039,28, 0,5646), (2040,04, 0,5371), (2040,80, 0,5200), (2041,56, 0,5063), (2042,32, 0,4891), (2043,08, 0,4754), (2043,84, 0,4583), (2044,60, 0,4480), (2045,36, 0,4377), (2046,12, 0,4309), (2046,88, 0,4240), (2047,64, 0,4206), (2048,40, 0,4137), (2049,16, 0,4103), (2049,92, 0,4069), (2050,68, 0,4069), (2051,44, 0,4034), (2052,20, 0,4000), (2052,96, 0,4000), (2053,72, 0,4000), (2054,48, 0,4000), (2055,24, 0,4000), (2056,00, 0,4000)

UNITS: dmnl

Environmental_Impact_Desalination.normal_marine_organism_generation_rate = 0,13

UNITS: fish/year

Environmental_Impact_Desalination.normal_marine_organism_generation_rate_2 = 0,15

UNITS: fish/year

Environmental_Impact_Desalination.normal_organism_lifespan_Aguillas = 18

UNITS: fish/year

Environmental_Impact_Desalination.normal_organism_lifespan_Benguela = 15

UNITS: fish/year

Environmental_Impact_Desalination.normal_revenue_value_fish_stock_Aguill

as =
Normal_Marine_Stocks.normal_marine_stock_aguillas*Rand_per_fish_Aguilla
s
UNITS: rand
Environmental_Impact_Desalination.normal_revenue_value_fish_stock_Bengu
ela =
Normal_Marine_Stocks.normal_marine_stock_benguela*Rand_per_fish_Beng
uela
UNITS: rand
Environmental_Impact_Desalination.normal_salinity = 370
UNITS: dmnl
Environmental_Impact_Desalination.potential_water_in_process =
Water_Supply_&_Demand.Desalination_Capacity*2,5
UNITS: ML/year
Environmental_Impact_Desalination.Rand_per_fish_Aguillas = 10
UNITS: rand/fish
Environmental_Impact_Desalination.Rand_per_fish_Benguela = 10
UNITS: rand/fish
Environmental_Impact_Desalination.salinity_residing_area =
1+(brine_density/normal_salinity)
UNITS: dmnl
Environmental_Impact_Desalination.storage_cost_per_ML = 20000
UNITS: rand/ml
Environmental_Impact_Desalination.Toxic_Waste(t) = Toxic_Waste(t - dt) +
(toxic_waste_production) * dt
INIT Environmental_Impact_Desalination.Toxic_Waste = 1
UNITS: ml
INFLOWS:
Environmental_Impact_Desalination.toxic_waste_production =
0,001*Water_Supply_&_Demand.Desalination_Capacity
UNITS: ml/year

****

Normal_Marine_Stocks.normal_birth_death:

****

Normal_Marine_Stocks.lifespan_marine_aguillas = 18

UNITS: fish/year

Normal_Marine_Stocks.lifespan_marine_benguela = 15

UNITS: fish/year

Normal_Marine_Stocks.nomal_births_benguela = 0,15

UNITS: fish/year

Normal_Marine_Stocks.normal_births_aguillas = 0,13

UNITS: fish/year

Normal_Marine_Stocks.normal_marine_stock_aguillas(t) = normal_marine_stock_aguillas(t - dt) + (normal_birth_rate_aguillas - normal_death_rate_aguillas) * dt

INIT Normal_Marine_Stocks.normal_marine_stock_aguillas = 2000000

UNITS: fish

INFLOWS:

Normal_Marine_Stocks.normal_birth_rate_aguillas = normal_births_aguillas*normal_marine_stock_aguillas

UNITS: fish/year

OUTFLOWS:

Normal_Marine_Stocks.normal_death_rate_aguillas = normal_marine_stock_aguillas/lifespan_marine_aguillas

UNITS: fish/year

Normal_Marine_Stocks.normal_marine_stock_benguela(t) = normal_marine_stock_benguela(t - dt) + (normal_birth_benguela - normal_deaths_benguela) * dt

INIT Normal_Marine_Stocks.normal_marine_stock_benguela = 2000000

UNITS: fish

INFLOWS:

Normal_Marine_Stocks.normal_birth_benguela = normal_marine_stock_benguela*nomal_births_benguela

UNITS: fish/year

OUTFLOWS:

Normal_Marine_Stocks.normal_deaths_benguela = normal_marine_stock_benguela/lifespan_marine_benguela

UNITS: fish/year

****

Water_Demand_Detailed.DEMAND_1:

****

Water_Demand_Detailed.budget_for_public_awareness_programs = Total_Water_Available*1

UNITS: dmnl

Water_Demand_Detailed.city_attractiveness_multiplier_1 = GRAPH(WCWDM_Managing_Threshold)

(0,000, 0,990), (0,600, 0,946), (1,200, 0,901), (1,800, 0,866), (2,400, 0,832), (3,000, 0,797), (3,600, 0,723), (4,200, 0,604), (4,800, 0,490), (5,400, 0,233), (6,000, 0,005)

UNITS: dmnl

Water_Demand_Detailed.demand_effect_through_URV = GRAPH(TIME)

(2006,00, 0,99474), (2007,00, 0,990265), (2008,00, 0,98579), (2009,00, 0,98158), (2010,00, 0,97779), (2011,00, 0,974), (2012,00, 0,97021), (2013,00, 0,96642), (2014,00, 0,96263), (2015,00, 0,959296666667), (2016,00, 0,955963333333), (2017,00, 0,95263), (2018,00, 0,948945), (2019,00, 0,94526), (2020,00, 0,94158), (2021,00, 0,93895), (2022,00, 0,93632), (2023,00, 0,933425), (2024,00, 0,93053), (2025,00, 0,92526), (2026,00, 0,923155), (2027,00, 0,92105), (2028,00, 0,918685), (2029,00, 0,91632), (2030,00, 0,91211), (2031,00, 0,910265), (2032,00, 0,90842), (2033,00, 0,90474), (2034,00, 0,90158), (2035,00, 0,90079), (2036,00, 0,9), (2037,00, 0,9), (2038,00, 0,9), (2039,00, 0,9), (2040,00, 0,9), (2041,00, 0,9), (2042,00, 0,9), (2043,00, 0,9), (2044,00, 0,9), (2045,00, 0,9), (2046,00, 0,9), (2047,00, 0,9), (2048,00, 0,9), (2049,00, 0,9), (2050,00, 0,9), (2051,00, 0,9), (2052,00, 0,9), (2053,00, 0,9), (2054,00, 0,9), (2055,00, 0,9), (2056,00, 0,9)

UNITS: dmnl/year

Water_Demand_Detailed.domestic_consumption_per_capita_per_year = WCWDM_Managing_Threshold

UNITS: dmnl

Water_Demand_Detailed."domestic_use_-_detailed" = (intrinsic_motivation_for_reduction_1+water_smart+tourist_water_consumption)*innovation_reduction_1

UNITS: dmnl

Water_Demand_Detailed.domesticUse_1 =
population_Cape_Town_1*domestic_consumption_per_capita_per_year-demand_effect_through_URV*years
UNITS: dmnl/years
Water_Demand_Detailed.innovation_reduction_1 = GRAPH(TIME)
(2006,00, 1,3689), (2007,00, 1,3689), (2008,00, 1,3689), (2009,00, 1,3694), (2010,00, 1,3700), (2011,00, 1,3700), (2012,00, 1,3700), (2013,00, 1,3700), (2014,00, 1,3700), (2015,00, 1,3700), (2016,00, 1,3700), (2017,00, 1,3700), (2018,00, 1,3689), (2019,00, 1,3677), (2020,00, 1,3666), (2021,00, 1,3643), (2022,00, 1,362725), (2023,00, 1,36115), (2024,00, 1,359575), (2025,00, 1,3580), (2026,00, 1,3557), (2027,00, 1,3534), (2028,00, 1,3511), (2029,00, 1,3494), (2030,00, 1,3477), (2031,00, 1,3460), (2032,00, 1,34345), (2033,00, 1,3409), (2034,00, 1,3383), (2035,00, 1,3357), (2036,00, 1,3340), (2037,00, 1,3323), (2038,00, 1,3303), (2039,00, 1,3283), (2040,00, 1,3249), (2041,00, 1,3220), (2042,00, 1,3200), (2043,00, 1,3180), (2044,00, 1,3146), (2045,00, 1,31315), (2046,00, 1,3117), (2047,00, 1,3089), (2048,00, 1,3069), (2049,00, 1,3020), (2050,00, 1,2997), (2051,00, 1,2911), (2052,00, 1,2891), (2053,00, 1,2871), (2054,00, 1,2820), (2055,00, 1,2780), (2056,00, 1,2700)
UNITS: dmnl
Water_Demand_Detailed.intrinsic_motivation_for_reduction_1 =
Total_Water_Available*1
UNITS: dmnl
Water_Demand_Detailed.irrigation_1 =
1*"projections_for_water_use_in_irrigation_/_liscencing"
UNITS: dmnl/year
Water_Demand_Detailed.lifespan = RANDOM(76 ; 79 ; 3)
UNITS: dmnl/year
Water_Demand_Detailed.net_birth_rate = 1,01
UNITS: dmnl/year
Water_Demand_Detailed.normal_amount_tourism = 1
UNITS: dmnl
Water_Demand_Detailed.normalcity_attractiveness = GRAPH(TIME)
(2006,00, 0,99789), (2007,00, 0,996315), (2008,00, 0,99474), (2009,00, 0,993461428571), (2010,00, 0,992182857143), (2011,00, 0,990904285714), (2012,00, 0,989625714286), (2013,00, 0,988347142857), (2014,00, 0,987068571429), (2015,00,

0,98579), (2016,00, 0,984094444444), (2017,00, 0,982398888889), (2018,00, 0,980703333333), (2019,00, 0,979007777778), (2020,00, 0,977312222222), (2021,00, 0,975616666667), (2022,00, 0,973921111111), (2023,00, 0,972225555556), (2024,00, 0,97053), (2025,00, 0,9686), (2026,00, 0,96667), (2027,00, 0,96474), (2028,00, 0,962895), (2029,00, 0,96105), (2030,00, 0,959646666667), (2031,00, 0,958243333333), (2032,00, 0,95684), (2033,00, 0,955), (2034,00, 0,95316), (2035,00, 0,951756666667), (2036,00, 0,950353333333), (2037,00, 0,94895), (2038,00, 0,946845), (2039,00, 0,94474), (2040,00, 0,943336666667), (2041,00, 0,941933333333), (2042,00, 0,94053), (2043,00, 0,938425), (2044,00, 0,93632), (2045,00, 0,934215), (2046,00, 0,93211), (2047,00, 0,930636), (2048,00, 0,929162), (2049,00, 0,927688), (2050,00, 0,926214), (2051,00, 0,92474), (2052,00, 0,922895), (2053,00, 0,92105), (2054,00, 0,915613333333), (2055,00, 0,910176666667), (2056,00, 0,9)

UNITS: dmnl

Water_Demand_Detailed.other_forms_of_water_use = 1*projections_water_used_for_mining_&_industry

UNITS: dmnl/year

Water_Demand_Detailed.population_Cape_Town_1(t) = population_Cape_Town_1(t - dt) + (births - deaths - "out-migration" - "in-migration") * dt

INIT Water_Demand_Detailed.population_Cape_Town_1 = 2000000

UNITS: dmnl

INFLOWS:

Water_Demand_Detailed.births = net_birth_rate

UNITS: dmnl/year

OUTFLOWS:

Water_Demand_Detailed.deaths = lifespan

UNITS: dmnl/year

Water_Demand_Detailed."out-migration" = yearly_outmigration

UNITS: dmnl/year

Water_Demand_Detailed."in-migration" = projected_yearly_migration_1*(normalcity_attractiveness-city_attractiveness_multiplier_1)

UNITS: dmnl/year

Water_Demand_Detailed.projected_yearly_migration_1 = 100

UNITS: dmnl/year

Water_Demand_Detailed."projections_for_water_use_in_irrigation_/_liscencing" = GRAPH(TIME)

(2006,00, 1,0000), (2007,00, 1,00473333333), (2008,00, 1,00946666667), (2009,00, 1,0142), (2010,00, 1,01893333333), (2011,00, 1,02366666667), (2012,00, 1,0284), (2013,00, 1,03371363636), (2014,00, 1,03902727273), (2015,00, 1,04434090909), (2016,00, 1,04965454545), (2017,00, 1,05496818182), (2018,00, 1,06028181818), (2019,00, 1,06559545455), (2020,00, 1,07090909091), (2021,00, 1,07622272727), (2022,00, 1,08153636364), (2023,00, 1,08685), (2024,00, 1,09216363636), (2025,00, 1,09747727273), (2026,00, 1,10279090909), (2027,00, 1,10810454545), (2028,00, 1,11341818182), (2029,00, 1,11873181818), (2030,00, 1,12404545455), (2031,00, 1,12935909091), (2032,00, 1,13467272727), (2033,00, 1,13998636364), (2034,00, 1,1453), (2035,00, 1,15475), (2036,00, 1,1642), (2037,00, 1,170525), (2038,00, 1,17685), (2039,00, 1,183175), (2040,00, 1,1895), (2041,00, 1,2021), (2042,00, 1,2116), (2043,00, 1,2195), (2044,00, 1,2258), (2045,00, 1,2337), (2046,00, 1,2447), (2047,00, 1,2542), (2048,00, 1,2637), (2049,00, 1,2716), (2050,00, 1,2842), (2051,00, 1,2921), (2052,00, 1,2984), (2053,00, 1,3000), (2054,00, 1,3000), (2055,00, 1,3000), (2056,00, 1,3000)

UNITS: dmnl/year

Water_Demand_Detailed.projections_water_used_for_mining_&_industry = GRAPH(TIME)

(2006,00, 0,0000), (2007,00, 1,0000), (2008,00, 1,0017), (2009,00, 1,0103), (2010,00, 1,01715), (2011,00, 1,0240), (2012,00, 1,02745), (2013,00, 1,0343), (2014,00, 1,0411), (2015,00, 1,0463), (2016,00, 1,0514), (2017,00, 1,05655), (2018,00, 1,0617), (2019,00, 1,0703), (2020,00, 1,0754), (2021,00, 1,0789), (2022,00, 1,08403333333), (2023,00, 1,08916666667), (2024,00, 1,0977), (2025,00, 1,1029), (2026,00, 1,1080), (2027,00, 1,1166), (2028,00, 1,1200), (2029,00, 1,1269), (2030,00, 1,1320), (2031,00, 1,1371), (2032,00, 1,1423), (2033,00, 1,1491), (2034,00, 1,1560), (2035,00, 1,1646), (2036,00, 1,1714), (2037,00, 1,1731), (2038,00, 1,1869), (2039,00, 1,1903), (2040,00, 1,1954), (2041,00, 1,2040), (2042,00, 1,2091), (2043,00, 1,2177), (2044,00, 1,2211), (2045,00, 1,2263), (2046,00, 1,2331), (2047,00, 1,2400), (2048,00, 1,2486), (2049,00, 1,2606), (2050,00, 1,2657), (2051,00, 1,2709), (2052,00, 1,2760), (2053,00, 1,2794), (2054,00, 1,2863), (2055,00, 1,2897), (2056,00, 1,2966)

UNITS: dmnl/year

Water_Demand_Detailed.Total_Water_Available(t) = Total_Water_Available(t - dt)

INIT Water_Demand_Detailed.Total_Water_Available = 1

UNITS: dmnl

Water_Demand_Detailed.totalwater_available(t) = totalwater_available(t - dt) + (water_demanded) * dt

INIT Water_Demand_Detailed.totalwater_available = 1

UNITS: dmnl

INFLOWS:

Water_Demand_Detailed.water_demanded = domesticUse_1+irrigation_1+other_forms_of_water_use

UNITS: dmnl/year

Water_Demand_Detailed.tourist_flow = normal_amount_tourism*Total_Water_Available

UNITS: dmnl

Water_Demand_Detailed.tourist_water_consumption = tourist_flow

UNITS: dmnl

Water_Demand_Detailed.water_smart = budget_for_public_awareness_programs

UNITS: dmnl

Water_Demand_Detailed.WCWDM_Managing_Threshold = IF Total_Water_Available<4000 THEN 0,5* Total_Water_Available ELSE Total_Water_Available

UNITS: dmnl

Water_Demand_Detailed.yearly_outmigration = 100

UNITS: dmnl/year

Water_Demand_Detailed.years = 0

UNITS: year

****

Water_Price.pricing:

****

Water_Price.cost_per_ML = 50000000

UNITS: rand

Water_Price.low_income = (Normalized_Cost_Desalinated_Water*-,14) *0,68

UNITS: rand

Water_Price.middle_income = (Normalized_Cost_Desalinated_Water*-,17) * 0,27

UNITS: rand

Water_Price.Normal_cost_Damwater = 5

UNITS: rand

Water_Price.Normalized_Cost_Desalinated_Water = URV_desal/Normal_cost_Damwater

UNITS: Rand

Water_Price.Price_Effect_Desal_on_Demand = (upper_income+middle_income+low_income)/3

UNITS: dmnl

Water_Price.upper_income = (Normalized_Cost_Desalinated_Water*-0,19)* 0,05

UNITS: rand

Water_Price.URV_desal = IF (TIME > 2022)THEN DELAY3(Desalination_Cost.total_cost_flow/cost_per_ML ; 8) ELSE 0

UNITS: rand

****

Water_Supply_&_Demand.Water_Stress:

****

Water_Supply_&_Demand.actual_capacity = Desalination_Capacity

UNITS: ML/year

Water_Supply_&_Demand.actual_water_reuse = potential_reusable_water*potential_water_reuse

UNITS: ML/year

Water_Supply_&_Demand.Aquifer_Water_Available(t) = Aquifer_Water_Available(t - dt) + (recharge - groundwater_extraction) * dt

INIT Water_Supply_&_Demand.Aquifer_Water_Available = 10000

UNITS: ML

INFLOWS:

Water_Supply_&_Demand.recharge =
(water_to_aquifers/groundwater_regeneration_delay)
UNITS: ML/year
OUTFLOWS:
Water_Supply_&_Demand.groundwater_extraction =
groundwater_cap_increase+Water_From_Boreholes
UNITS: ML/year
Water_Supply_&_Demand.assurance_of_supply = 1
UNITS: dmnl
Water_Supply_&_Demand.Avg_Desalination_Plant_Lifespan_With_Maintenance = IF(No_maintenance_switch=1) THEN avg_lifespan_without_maintenance ELSE 1000
UNITS: year
Water_Supply_&_Demand.avg_lifespan_without_maintenance = 20
UNITS: dmnl
Water_Supply_&_Demand.capacity_adjustment_time = 1
UNITS: dmnl
Water_Supply_&_Demand.change_in_water_extraction =
GRAPH(water_supply_gap*extraction_multiplier)
(1,0, 0,0), (8,98, 0,0), (16,96, 0,0), (24,94, 0,0), (32,92, 0,0), (40,9, 0,0), (48,88, 0,0), (56,86, 0,0), (64,84, 0,0), (72,82, 0,0), (80,8, 4,6), (88,78, 13,7), (96,76, 27,4), (104,74, 36,6), (112,72, 50,3), (120,7, 59,4), (128,68, 68,6), (136,66, 91,4), (144,64, 118,9), (152,62, 137,1), (160,6, 150,9), (168,58, 160,0), (176,56, 169,1), (184,54, 182,9), (192,52, 192,0), (200,5, 214,9), (208,48, 228,6), (216,46, 242,3), (224,44, 256,0), (232,42, 274,3), (240,4, 283,4), (248,38, 301,7), (256,36, 320,0), (264,34, 338,3), (272,32, 356,6), (280,3, 370,3), (288,28, 388,6), (296,26, 406,9), (304,24, 429,7), (312,22, 443,4), (320,2, 470,9), (328,18, 489,1), (336,16, 539,4), (344,14, 566,9), (352,12, 589,7), (360,1, 621,7), (368,08, 649,1), (376,06, 690,3), (384,04, 736,0), (392,02, 800,0), (400,0, 800,0)
UNITS: dmnl
Water_Supply_&_Demand.climate_change = GRAPH(TIME)
(2006,00, 0,9957), (2007,00, 0,9931), (2008,00, 0,9914), (2009,00, 0,9889), (2010,00, 0,9871), (2011,00, 0,9837), (2012,00, 0,9820), (2013,00, 0,9803), (2014,00, 0,9769), (2015,00, 0,9760), (2016,00, 0,9734), (2017,00, 0,9726), (2018,00, 0,9674), (2019,00,

0,96525), (2020,00, 0,9606), (2021,00, 0,9589), (2022,00, 0,9546), (2023,00, 0,9537), (2024,00, 0,9477), (2025,00, 0,9451), (2026,00, 0,9417), (2027,00, 0,9357), (2028,00, 0,9340), (2029,00, 0,9280), (2030,00, 0,9254), (2031,00, 0,9229), (2032,00, 0,9194), (2033,00, 0,9177), (2034,00, 0,9143), (2035,00, 0,9066), (2036,00, 0,9031), (2037,00, 0,9014), (2038,00, 0,8989), (2039,00, 0,8971), (2040,00, 0,8954), (2041,00, 0,8929), (2042,00, 0,8894), (2043,00, 0,8843), (2044,00, 0,8791), (2045,00, 0,8783), (2046,00, 0,8766), (2047,00, 0,8757), (2048,00, 0,8714), (2049,00, 0,8689), (2050,00, 0,8654), (2051,00, 0,8637), (2052,00, 0,8594), (2053,00, 0,8569), (2054,00, 0,8543), (2055,00, 0,8526), (2056,00, 0,8500)

UNITS: dmnl

Water_Supply_&_Demand.dam_flow = IF (TIME<2018) THEN historic_dam_cap ELSE precipitation

UNITS: ML/year

Water_Supply_&_Demand.Desalination_Capacity(t) = Desalination_Capacity(t - dt) + (Desal_Capacity_Increase - Desalination_Plant_Depreciation) * dt

INIT Water_Supply_&_Demand.Desalination_Capacity = 1

UNITS: ML

INFLOWS:

Water_Supply_&_Demand.Desal_Capacity_Increase = Threshold_Augmentation_Desalination

UNITS: ML/year

OUTFLOWS:

Water_Supply_&_Demand.Desalination_Plant_Depreciation = Desalination_Capacity/Avg_Desalination_Plant_Lifespan_With_Maintenance

UNITS: ML/year

Water_Supply_&_Demand.desired_capacity = 150

UNITS: ML/year

Water_Supply_&_Demand.desired_extra_megalitres_desalination = 1

UNITS: dmnl

Water_Supply_&_Demand.domdemand = GRAPH(TIME)

(2006,00, 670), (2006,50, 830), (2007,00, 720), (2007,50, 820), (2008,00, 670), (2008,50, 780), (2009,00, 850), (2009,50, 740), (2010,00, 660), (2010,50, 850), (2011,00, 630), (2011,50, 750), (2012,00, 850), (2012,50, 700), (2013,00, 780), (2013,50, 660), (2014,00, 790), (2014,50, 590), (2015,00, 670), (2015,50, 510), (2016,00, 580), (2016,50, 460), (2017,00, 510), (2017,50, 410), (2018,00, 340), (2018,50, 440), (2019,00, 410), (2019,50, 400), (2020,00, 490), (2020,50, 430), (2021,00, 540), (2021,50, 470), (2022,00, 580), (2022,50, 520), (2023,00, 630), (2023,50, 560), (2024,00, 680), (2024,50, 600), (2025,00, 720), (2025,50, 650), (2026,00, 770), (2026,50, 690), (2027,00, 800), (2027,50, 730), (2028,00, 830), (2028,50, 770), (2029,00, 870), (2029,50, 820), (2030,00, 910), (2030,50, 870), (2031,00, 940), (2031,50, 880), (2032,00, 980), (2032,50, 940), (2033,00, 1000), (2033,50, 960), (2034,00, 1010), (2034,50, 1000), (2035,00, 1060), (2035,50, 1010), (2036,00, 1070), (2036,50, 1060), (2037,00, 1130), (2037,50, 1080), (2038,00, 1120), (2038,50, 1160), (2039,00, 1110), (2039,50, 1170), (2040,00, 1160), (2040,50, 1210), (2041,00, 1150), (2041,50, 1230), (2042,00, 1180), (2042,50, 1250), (2043,00, 1250), (2043,50, 1190), (2044,00, 1290), (2044,50, 1270), (2045,00, 1250), (2045,50, 1330), (2046,00, 1250), (2046,50, 1310), (2047,00, 1260), (2047,50, 1360), (2048,00, 1340), (2048,50, 1310), (2049,00, 1420), (2049,50, 1340), (2050,00, 1430), (2050,50, 1390), (2051,00, 1440), (2051,50, 1450), (2052,00, 1380), (2052,50, 1450), (2053,00, 1450), (2053,50, 1420), (2054,00, 1450), (2054,50, 1440), (2055,00, 1450), (2055,50, 1450), (2056,00, 1420)

UNITS: ML/year

Water_Supply_&_Demand.effect_of_ratio_on_overflow = GRAPH(ratio_of_potential_to_max_dam_water)

(0,000, 1,000), (0,0333333333333, 1,000), (0,0666666666667, 1,000), (0,100, 1,000), (0,133333333333, 1,000), (0,166666666667, 1,000), (0,200, 1,000), (0,233333333333, 1,000), (0,266666666667, 1,000), (0,300, 1,000), (0,333333333333, 1,000), (0,366666666667, 1,000), (0,400, 1,000), (0,433333333333, 1,000), (0,466666666667, 1,000), (0,500, 1,000), (0,533333333333, 1,000), (0,566666666667, 1,000), (0,600, 1,000), (0,633333333333, 1,000), (0,666666666667, 1,000), (0,700, 1,000), (0,733333333333, 1,000), (0,766666666667, 1,000), (0,800, 1,000), (0,833333333333, 1,000), (0,866666666667, 1,000), (0,900, 1,000), (0,933333333333, 1,000), (0,966666666667, 0,963), (1,000, 0,000)

UNITS: dmnl/year

Water_Supply_&_Demand.extraction_multiplier = 1

UNITS: dmnl

Water_Supply_&_Demand.flow_from_aquifers = IF (Aquifer_Water_Available > 4000) THEN DELAY1(threshold_water_augmentation_groundwater ; 1)

ELSE DELAY1(0,5* threshold_water_augmentation_groundwater ; 1)
UNITS: ML/year
Water_Supply_&_Demand.gap_conversion_to_reuse =
GRAPH(water_supply_gap)
(0,0, 0,0034), (60,0, 0,0240), (120,0, 0,0686), (180,0, 0,0994), (240,0, 0,1371), (300,0, 0,1886), (360,0, 0,2503), (420,0, 0,3291), (480,0, 0,3977), (540,0, 0,4903), (600,0, 0,6000)
UNITS: dmnl
Water_Supply_&_Demand.gradual_desal_increase_switch = 0
UNITS: dmnl
Water_Supply_&_Demand.groundwater_cap_increase =
DELAY1(threshold_water_augmentation_groundwater; 1)
UNITS: ML/year
Water_Supply_&_Demand.groundwater_regeneration_delay = 20
UNITS: dmnl
Water_Supply_&_Demand.historic_dam_cap = GRAPH(TIME)
(2006,00, 800,000), (2006,25531915, 650,000), (2006,5106383, 730,000), (2006,76595745, 910,000), (2007,0212766, 810,000), (2007,27659574, 680,000), (2007,53191489, 720,000), (2007,78723404, 880,000), (2008,04255319, 790,000), (2008,29787234, 650,000), (2008,55319149, 760,000), (2008,80851064, 910,000), (2009,06382979, 810,000), (2009,31914894, 640,000), (2009,57446809, 750,000), (2009,82978723, 900,000), (2010,08510638, 810,000), (2010,34042553, 640,000), (2010,59574468, 750,000), (2010,85106383, 900,000), (2011,10638298, 750,000), (2011,36170213, 550,000), (2011,61702128, 600,000), (2011,87234043, 810,000), (2012,12765957, 700,000), (2012,38297872, 500,000), (2012,63829787, 500,000), (2012,89361702, 900,000), (2013,14893617, 770,000), (2013,40425532, 600,000), (2013,65957447, 710,000), (2013,91489362, 910,000), (2014,17021277, 810,000), (2014,42553191, 700,000), (2014,68085106, 810,000), (2014,93617021, 900,000), (2015,19148936, 750,000), (2015,44680851, 560,000), (2015,70212766, 450,000), (2015,95744681, 670,000), (2016,21276596, 500,000), (2016,46808511, 320,000), (2016,72340426, 280,000), (2016,9787234, 550,000), (2017,23404255, 410,000), (2017,4893617, 250,000), (2017,74468085, 200,000), (2018,00, 320,000)
UNITS: ML/year
Water_Supply_&_Demand.historic_domestic_demand = GRAPH(IF (TIME <

2012) THEN (900+(SINWAVE(200; 1))) ELSE TIME)
(2012,000, 770), (2012,26086957, 1040), (2012,52173913, 780), (2012,7826087, 850), (2013,04347826, 1110), (2013,30434783, 1023), (2013,56521739, 840), (2013,82608696, 880), (2014,08695652, 1044,2), (2014,34782609, 830), (2014,60869565, 910), (2014,86956522, 1111), (2015,13043478, 898,9), (2015,39130435, 1140), (2015,65217391, 810), (2015,91304348, 980), (2016,17391304, 970), (2016,43478261, 760), (2016,69565217, 820), (2016,95652174, 810), (2017,2173913, 760), (2017,47826087, 703,4), (2017,73913043, 734,3), (2018,000, 703,4)

UNITS: ML/year

Water_Supply_&_Demand.individual_boreholes = GRAPH(IF switch=1 THEN water_supply_gap ELSE 0)
(50,0, 0,00), (105,0, 0,00), (160,0, 0,00), (215,0, 2,00), (270,0, 5,43), (325,0, 9,71), (380,0, 15,71), (435,0, 19,43), (490,0, 30,86), (545,0, 48,86), (600,0, 50,00)

UNITS: ML/year

Water_Supply_&_Demand.maximum_dam_water = 983+("potential_dam_expansions_capacity_(Voelvlei)")

UNITS: ML

Water_Supply_&_Demand.No_maintenance_switch = 0

UNITS: dmnl

Water_Supply_&_Demand.percentage_covered_by_desal = Desalination_Capacity/Water_Available

UNITS: dmnl

Water_Supply_&_Demand."potential_dam_expansions_capacity_(Voelvlei)" = STEP(200 ; 2026)

UNITS: ML/year

Water_Supply_&_Demand.potential_reusable_water = Water_Available

UNITS: ML

Water_Supply_&_Demand.potential_water_reuse = IF(switch_water_reuse =1) AND (TIME >2018) THEN (SMTH3(gap_conversion_to_reuse; 2)) ELSE 0

UNITS: dmnl

Water_Supply_&_Demand.precipitation = 0,09*rainfall_scenario's_in_catchment_area

UNITS: ML/year

Water_Supply_&_Demand.pricing_effect_by_desal =
percentage_covered_by_desal*Water_Price.Price_Effect_Desal_on_Demand
UNITS: dmnl
Water_Supply_&_Demand.rainfall_scenario's_in_catchment_area =
NORMAL(8000; (1000*assurance_of_supply); 4)*climate_change
UNITS: ML/year
Water_Supply_&_Demand.ratio_of_potential_to_max_dam_water =
maximum_dam_water/Water_Available
UNITS: dmnl
Water_Supply_&_Demand.single_desalination_implementation =
DELAY1(PULSE((150+desired_extra_megalitres_desalination); 2018 ; 100); 1)
UNITS: ML/year
Water_Supply_&_Demand."SINWAVE_2006-2012" = IF TIME <2012 THEN
750+SINWAVE(50; 1) ELSE 0
UNITS: ML/year
Water_Supply_&_Demand.switch = 1
UNITS: dmnl
Water_Supply_&_Demand.switch_desalination = 1
UNITS: dmnl
Water_Supply_&_Demand.switch_groundwater = 1
UNITS: dmnl
Water_Supply_&_Demand.switch_water_reuse = 1
UNITS: dmnl
Water_Supply_&_Demand.Threshold_Augmentation_Desalination = IF
switch_desalination=1 AND (TIME >2018) THEN (IF
gradual_desal_increase_switch=1 THEN (desired_capacity-
actual_capacity/capacity_adjustment_time) ELSE
single_desalination_implementation) ELSE 0
UNITS: ML/year
Water_Supply_&_Demand.threshold_water_augmentation_groundwater = IF
switch_groundwater=1 AND (TIME >2016) THEN
(DELAY3(change_in_water_extraction; 1)) ELSE 0
UNITS: dmnl
Water_Supply_&_Demand.total_historic_demand = IF (TIME <2012) THEN

"SINWAVE_2006-2012" ELSE historic_domestic_demand

UNITS: ML/year

Water_Supply_&_Demand.Water_Available(t) = Water_Available(t - dt) + (incoming_water_supply - Total_Water_Supplied - overflow_1) * dt

INIT Water_Supply_&_Demand.Water_Available = 800

UNITS: ML

INFLOWS:

Water_Supply_&_Demand.incoming_water_supply = dam_flow+Desalination_Capacity+actual_water_reuse+flow_from_aquifers

UNITS: ml/year

OUTFLOWS:

Water_Supply_&_Demand.Total_Water_Supplied = MIN(Water_Available ; water_demand)

UNITS: ml/year

Water_Supply_&_Demand.overflow_1 = Water_Available*effect_of_ratio_on_overflow

UNITS: ml/year

Water_Supply_&_Demand.water_demand = IF (TIME <2018) THEN total_historic_demand ELSE (domdemand*(1+pricing_effect_by_desal))*water_restrictions_thresholds

UNITS: ML/year

Water_Supply_&_Demand.Water_From_Boreholes(t) = Water_From_Boreholes(t - dt) + (borehole_capacity_increase) * dt

INIT Water_Supply_&_Demand.Water_From_Boreholes = 1

UNITS: ML

INFLOWS:

Water_Supply_&_Demand.borehole_capacity_increase = IF (TIME<2016) THEN 0 ELSE individual_boreholes

UNITS: ML/year

Water_Supply_&_Demand.water_restrictions_thresholds = IF (Water_Available < 600) THEN (0,90) ELSE (IF Water_Available <500 THEN 0,85 ELSE (IF Water_Available<250 THEN 0,75 ELSE 1))

UNITS: dmnl

Water_Supply_&_Demand.water_supply_gap = MAX(0; water_demand-

Total_Water_Supplied)

UNITS: ML/year

Water_Supply_&_Demand.water_to_aquifers =

0,04*rainfall_scenario's_in_catchment_area

UNITS: ML/year

{ The model has 242 (242) variables (array expansion in parens).

In root model and 10 additional modules with 8 sectors.

Stocks: 17 (17) Flows: 29 (29) Converters: 196 (196)

Constants: 64 (64) Equations: 161 (161) Graphicals: 36 (36)

There are also 56 expanded macro variables.

}

Annex VIII. Validation – extensive

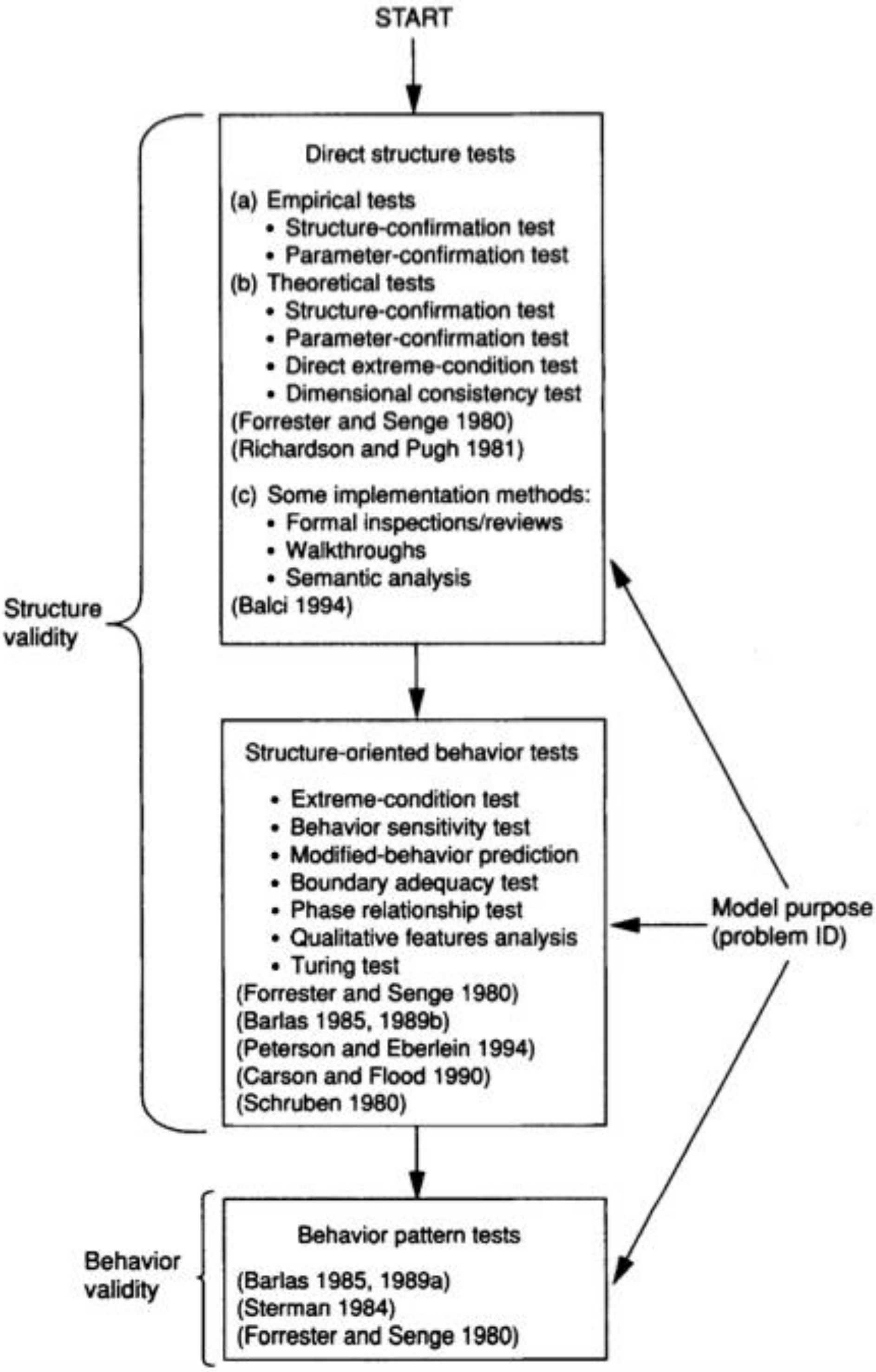


FIGURE 1: OVERVIEW OF TESTS FOR MODEL VALIDATION (BARLAS, 1996)

Tests of model structure

The tests of model structure, are essentially tests that assess structure and parameters directly .These tests make sure that model structure and parameters do not contradict existing knowledge. Testing involves directly checking on the structure and reaching consensus on these structure, either through digital verification or through stakeholder input. The created ACTDesal model has been put subject to multiple of the tests suggested by Barlas (1996).

Structure Verification test

In this structure verification test, it is necessary to verify with modelers, followed by the verification with experts whether the model represents the real system (Barlas, 2008). In the case of ACTDesal, the model has been largely discussed technically with Dr. J. Clifford Holmes, Dr. R. MacDonald, PhD. candidate B. Schoenberg, Dr. A. Botha and PhD. candidate P. Currie. Although some more than others, all agreed the modeling structure to be technically representable; suggestions on initial circularity were taken into account and reiterated. More importantly, model structure has been constantly shown to expert stakeholders, whereas after showing the model the question whether this model is representing the real system on their particular expertise was asked. For some of the stakeholders, some iterations had to be made. In the second round of conversations these stakeholders were asked the same question again, where all of them responded that the model was representing their field of expertise within the context of the model.

Parameter Verification test

In the parameter verification test, one argues whether the model has plausible values. For this test, the context of the South African state of affairs is important. It has proven very difficult to find accurate data on the public web; either because the CCT does not accurately document their data or do not store this data on publicly shared websites (Winter, 2018). The parameters which are present are being represented in such a way that there is small room for variance and outliers; to verify the parameters on data was in several cases not possible. Nevertheless, for verification of these parameters, the research adapted a qualitative approach: Parameters which were considered an ‘educated guess’ became subject to the mental model of multiple stakeholders – whereas an average of these values was taken for parametrization.

Dimensional Consistency test

The model was made unit consistent; a total of three larger units were introduced: ML, fish and rand. The model has been made sure to have no sign of any variables that were present for the sake of unit consistency; all the behavior generated is therefore dimensionally consistent.

Tests of model behavior

Tests of model behavior are tests that evaluate the adequacy of the model structure through analysis of behavior that is generated by the structure. It is a form of 'observing the output' rather than 'checking the consistency of the input'. For this model, tests of model behavior includes a test of symptom generation, extreme policy test and most importantly, a behavior reproduction test.

Symptom generation test

Simply put, this test is a test of showing the model in the current situation leads to a problematic situation. In terms of water availability, a system failure was considered when water demand would govern the water availability stock (Graph X). With this graph, it can be concluded that in current situations the modeled behavior leads to a problematic situation.

Extreme Policy test

This test seeks answer the alteration of a policy statement in an extreme way: It answers the question whether the model behaves as expected with the alteration of a policy statement in an extreme way. In the model, this can be done by either intensifying the amount of augmentation or decreasing the effect of desalination on water demand through extreme subsidies (1%). Subsequently, in Figure 48, augmentation matters have been intensified by 3, whereas the model corresponds to this behavior in the expected way; there is no single sense of water scarcity in the period until 2056. Furthermore, by decreasing the government tariff to 1% the system reacts accordingly; there is an increase in water demand.

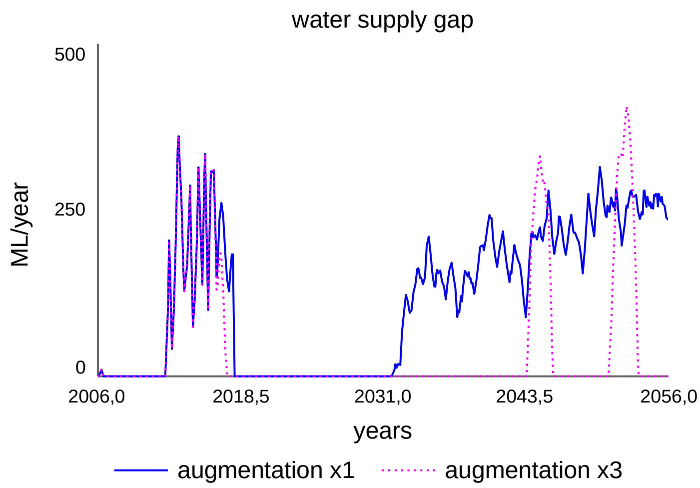


FIGURE 2: INCREASE OF AUGMENTATION INTERVENTION CAPACITY (MULTIPLIED BY 3)

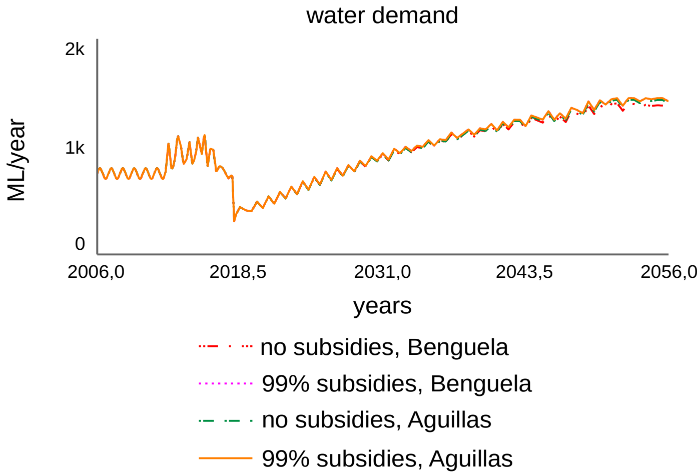


FIGURE 3: INCREASE OF GOVERNMENT TARIFF BY 99% (CITIZENS ONLY PAY 1% OF TOTAL EXTRA COSTS OF DESALINATION – CONTROLLED FOR BOTH CURRENTS.

Behavior Reproduction test

The behavior reproduction test is a test against its reference mode: It tries to capture the adequacy in match to the model-generated behavior and the observed (real-world) behavior. The answer to this question is twofold. First his model represents the historical pattern in the model in both supply and demand; the model responds adequately in the current water pattern. Since the water drought was an event with a probability of only 1 in 1000 (CSAG, 2018) it was necessary to capture the behavior in a historical manner.

Secondly, the model adapts the ‘smaller model’ which is verified by all stakeholders to be a right representation as a reference mode. Putting the current detailed model next to the smaller model shows the accuracy of the produced behavior of the most relevant variables to the reference mode (Figure X, Y and Z). Since hardly any data had been introduced for the ACTDesal project to be of usefulness, the creation of a reference mode through consensus was an unavoidable step.

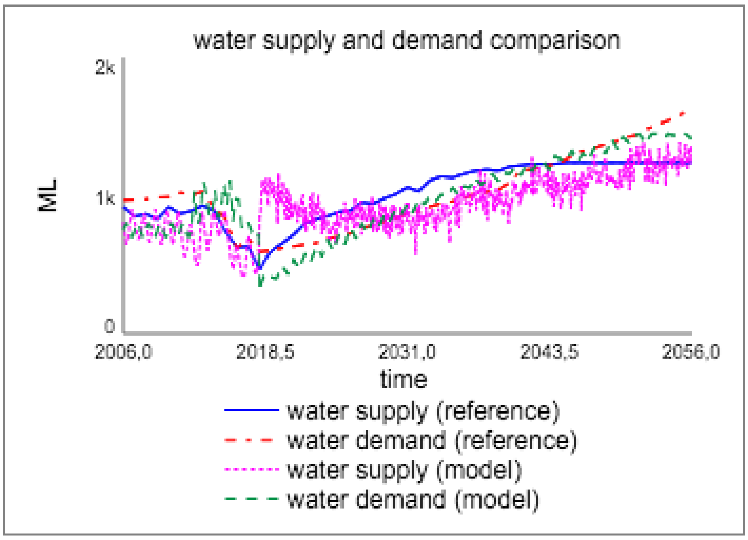


FIGURE 4: COMPARISON WATER SUPPLY AND DEMAND TO REFERENCE MODE

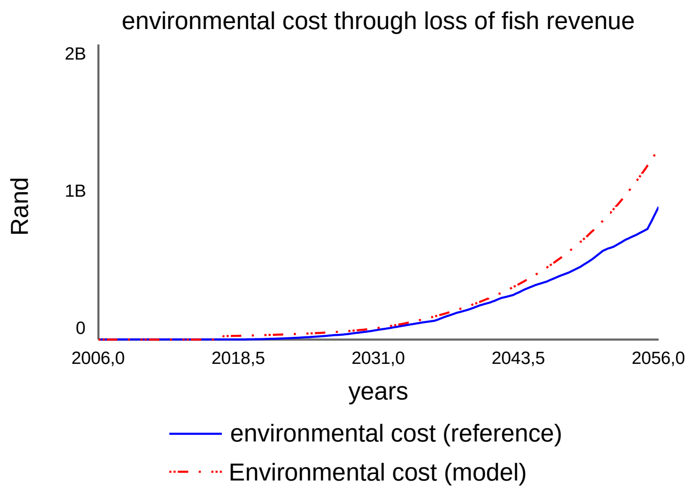


FIGURE 5COMPARISON DESALINATED ENVIRONMENTAL COST TO REFERENCE MODE

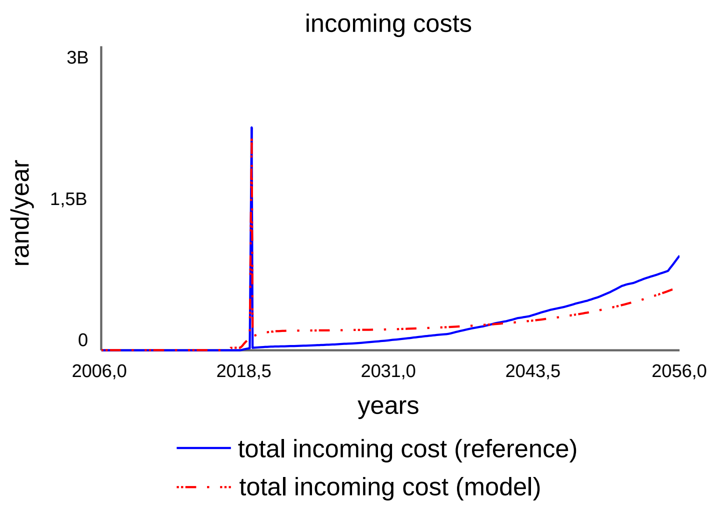


FIGURE 6: COMPARISON TOTAL DESALINATED COST TO REFERENCE MODE

Annex IX: decision points, scenario-setting

Decision point 1: Augmentation – Demand and supply on population

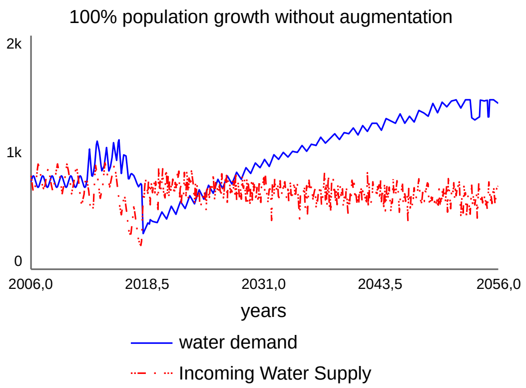


FIGURE 1A. SUPPLY AND DEMAND, Y 100% POPULATION GROWTH, NO AUGMENTATION

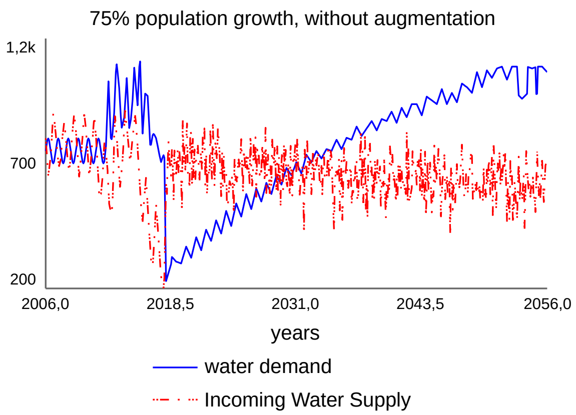


FIGURE 1B. SUPPLY AND DEMAND, 75% POPULATION GROWTH, NO AUGMENTATION

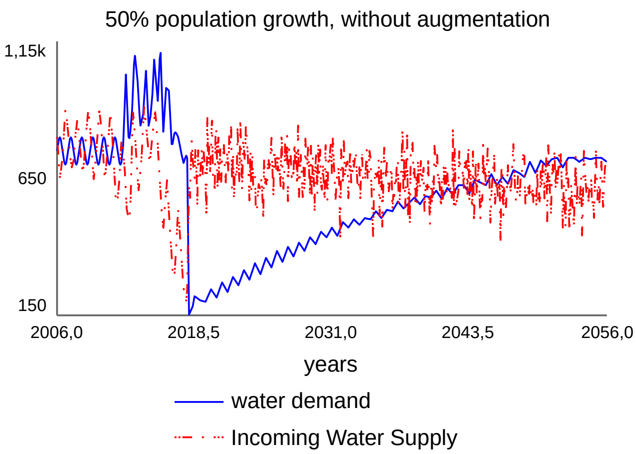


FIGURE 1C. SUPPLY AND DEMAND, 50% POPULATION GROWTH, NO AUGMENTATION

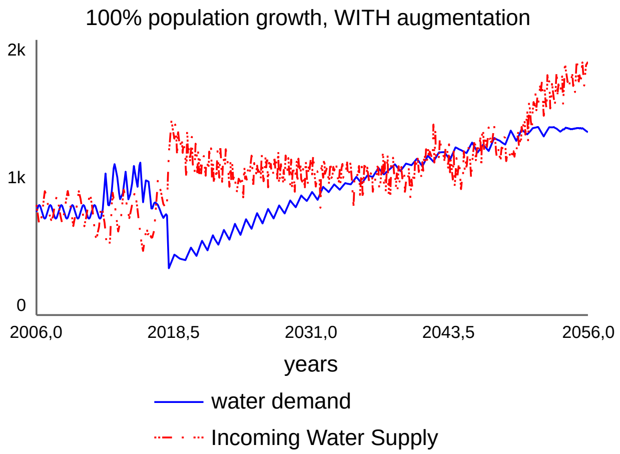


Figure 1D. Supply and demand, 100% population growth, proposed augmentation

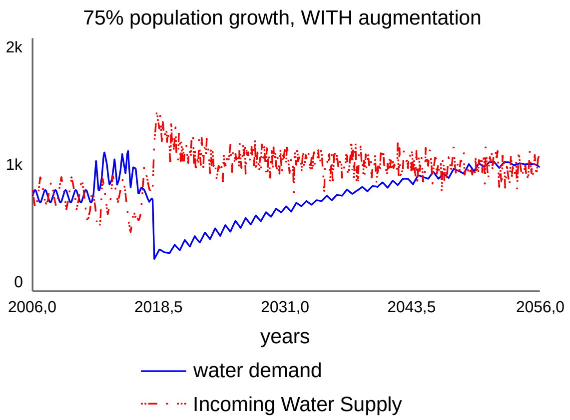


Figure 1E. Supply and demand, 75% population growth, proposed augmentation

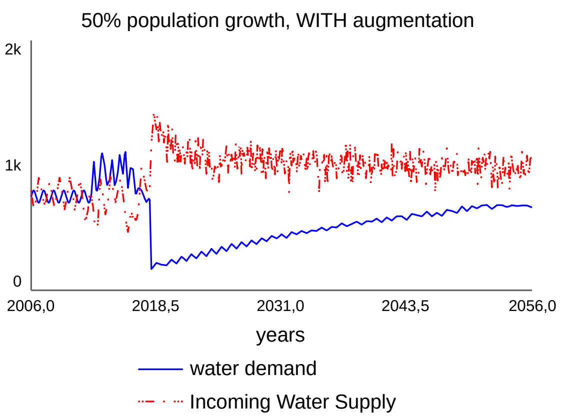


Figure 1F. Supply and demand, 50% population growth, proposed augmentation

Decision point 1B: Augmentation on climate

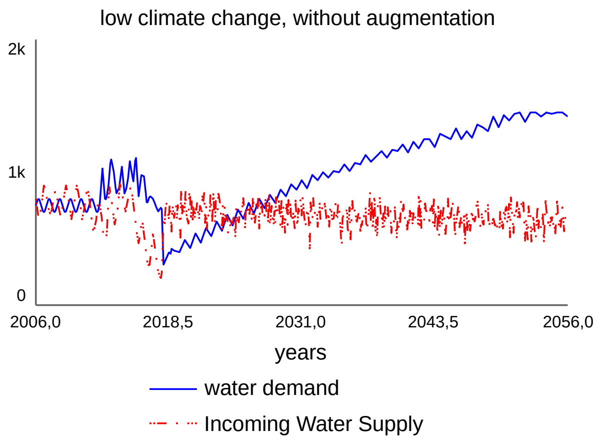


Figure 2A. Supply and demand, low climate change (10%), without augmentation

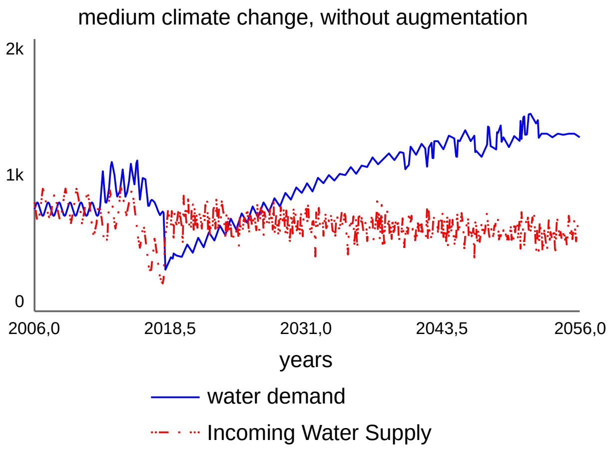


Figure 2B. Supply and demand, medium climate change (20%), without augmentation

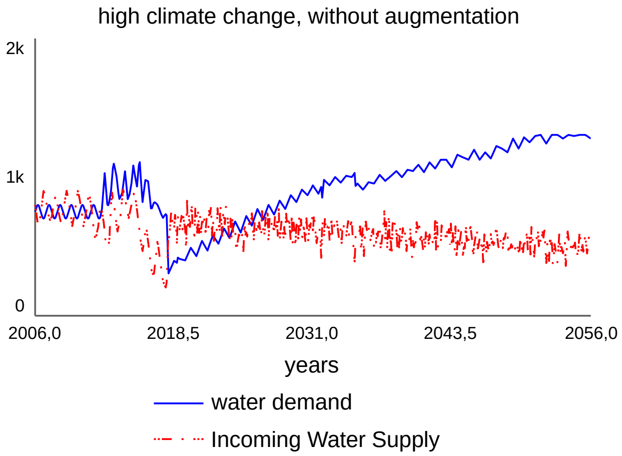


Figure 2C. Supply and demand, high climate change (30%), without augmentation

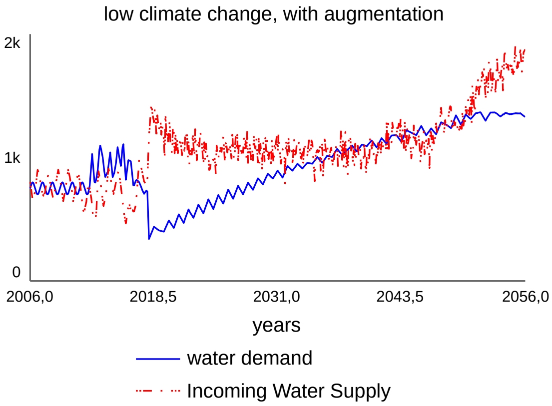


Figure 2D. Supply and demand, low climate change (10%), with augmentation

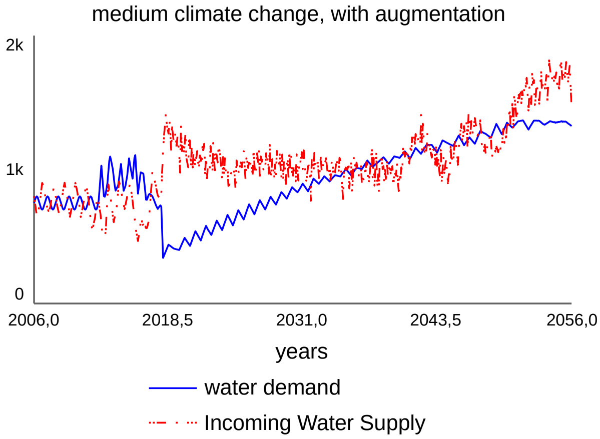


Figure 2E. Supply and demand, medium climate change (20%), with augmentation

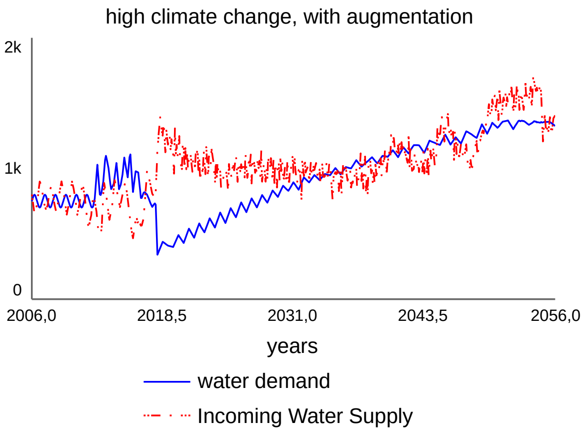


Figure 2F. Supply and demand, high climate change (30%), with augmentation

Decision point 1C: desalination installed capacity

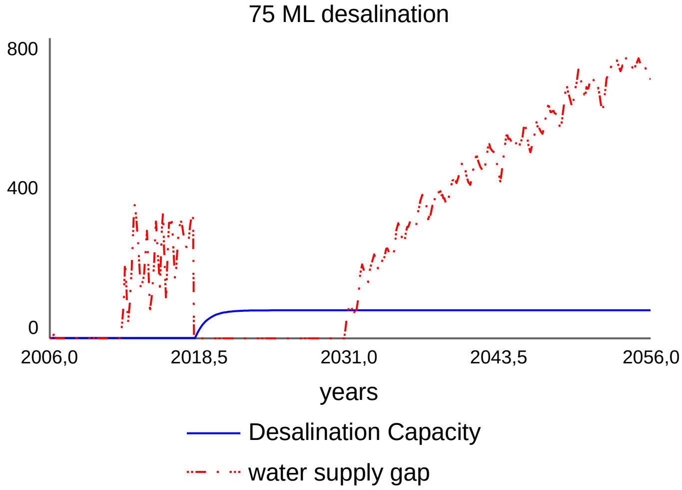


Figure 3A. Water gap and desalination (75 ML)

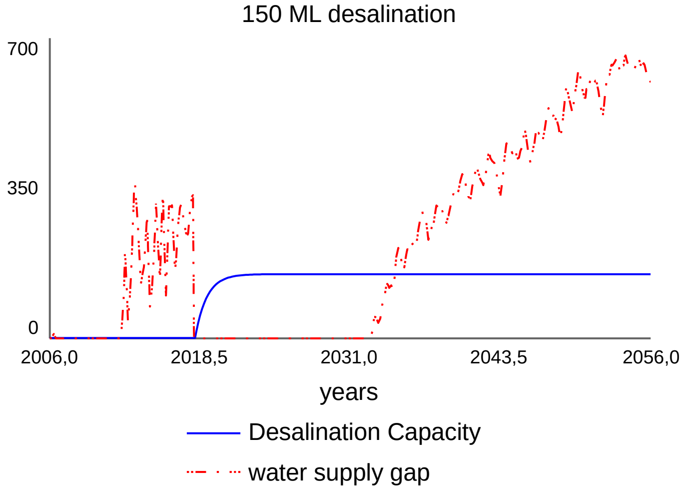


Figure 3B. Water gap and desalination (150 ML)

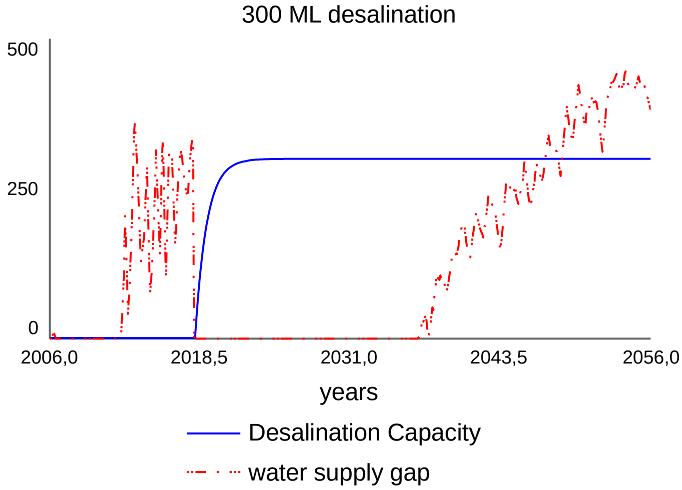


Figure 3C. Water gap and desalination (300 ML)

Decision point 2: Quantity of desalination

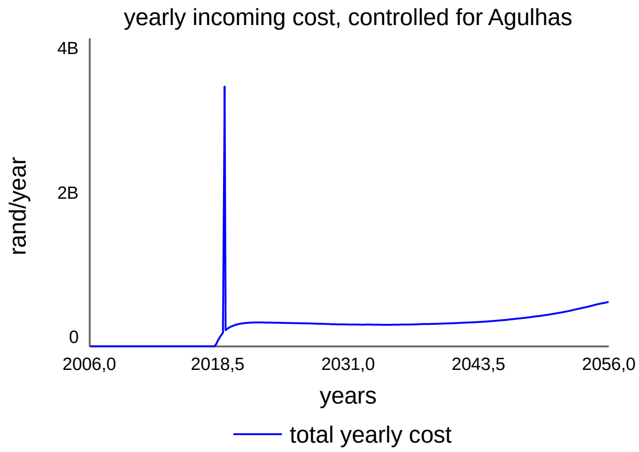


Figure 4A. Total cost, controlled for Agulhas

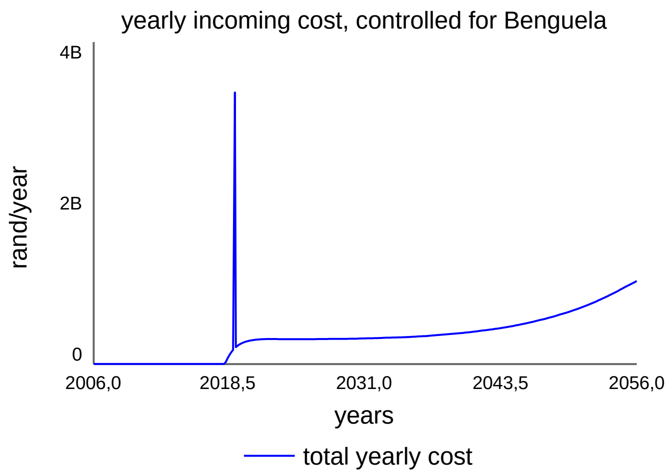


Figure 4B. Total cost, controlled for Benguela

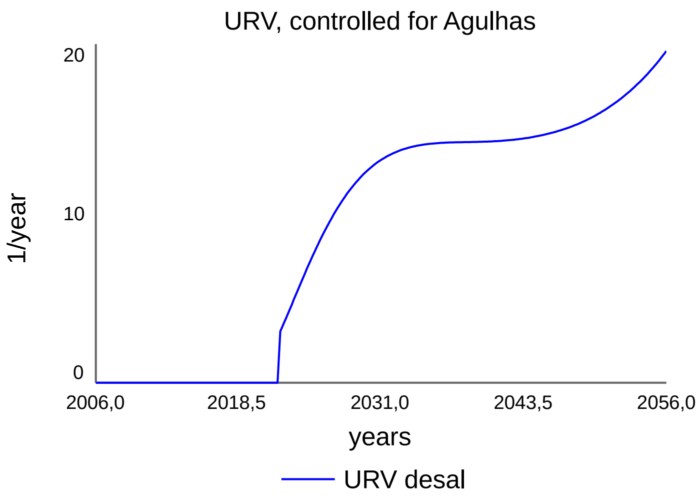


Figure 4C. URV, controlled for Agulhas

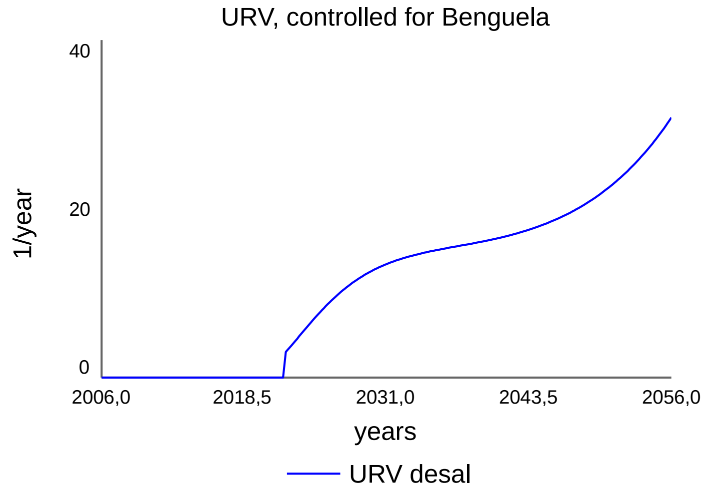


Figure 4D. URV, controlled for Benguela

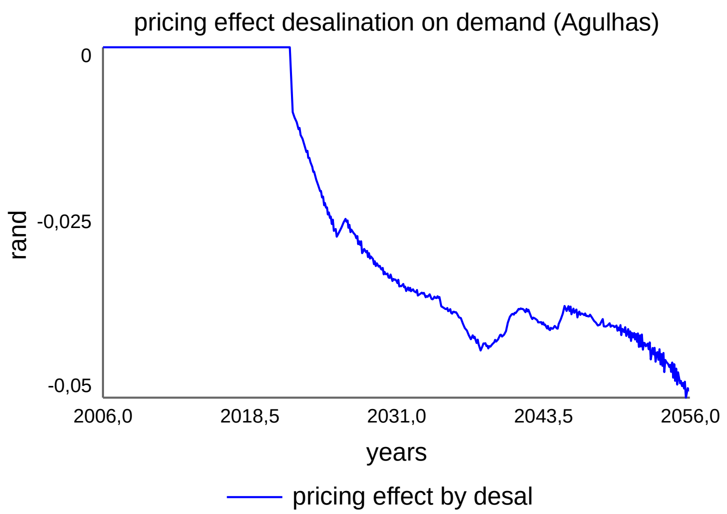


Figure 4E. Price effects on demand, controlled for Agulhas

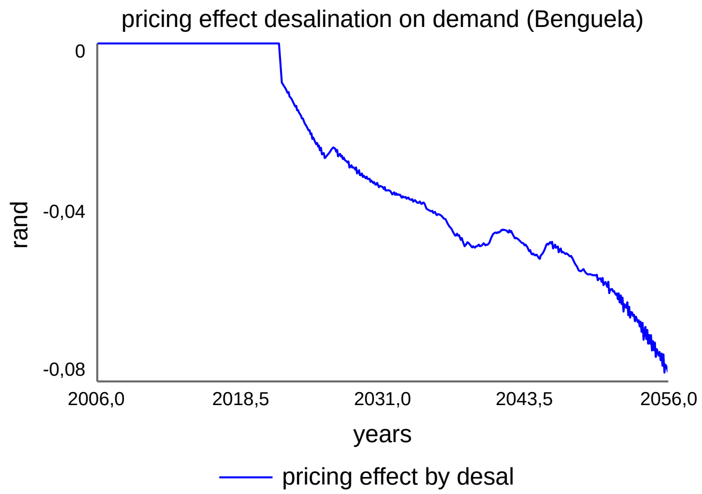


Figure 4F. Price effects on demand, controlled for Benguela

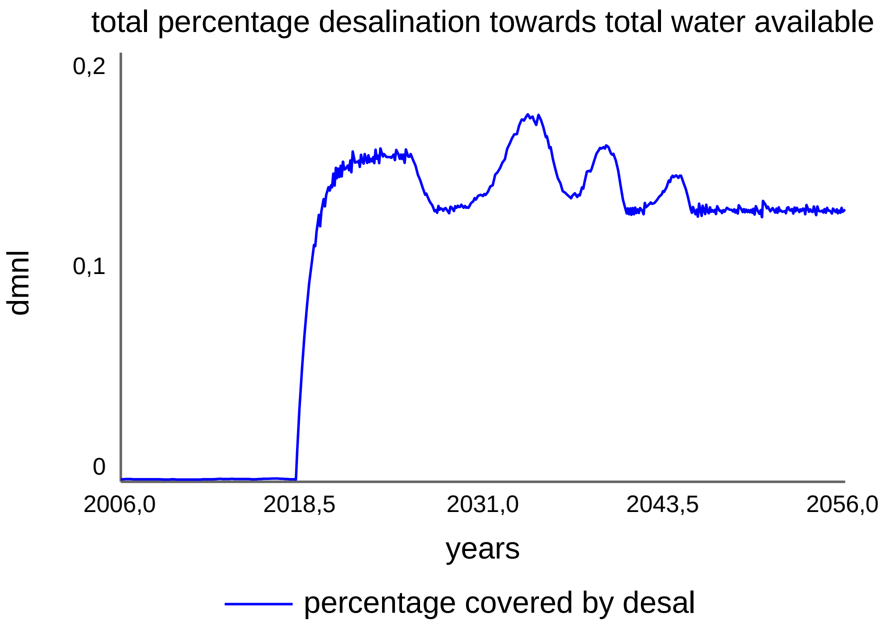


Figure 4G. total percentage of desalination towards total supply

Decision point 3: Timing desalination

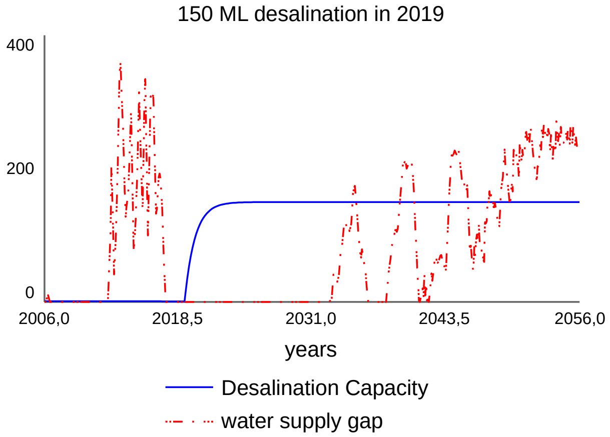


Figure 5A: water gap and desalination for implementation in 2019 (accounting for all other proposed augmentation intervention)

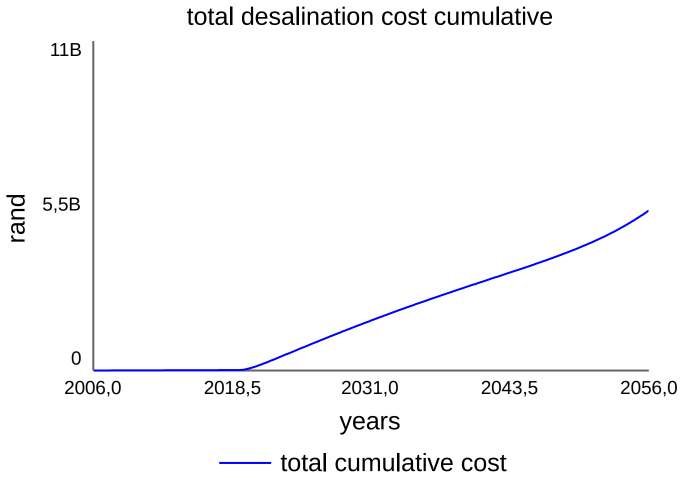


Figure 5B: total cost of desalination for implementation in 2019 (Agulhas)

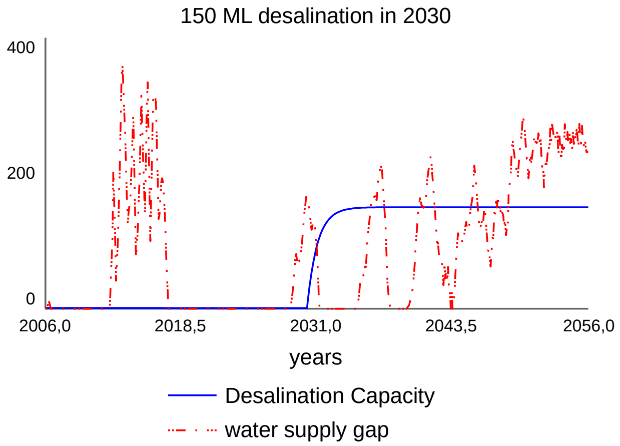


Figure 5C: water gap and desalination for implementation in 2030 (accounting for all other proposed augmentation intervention)

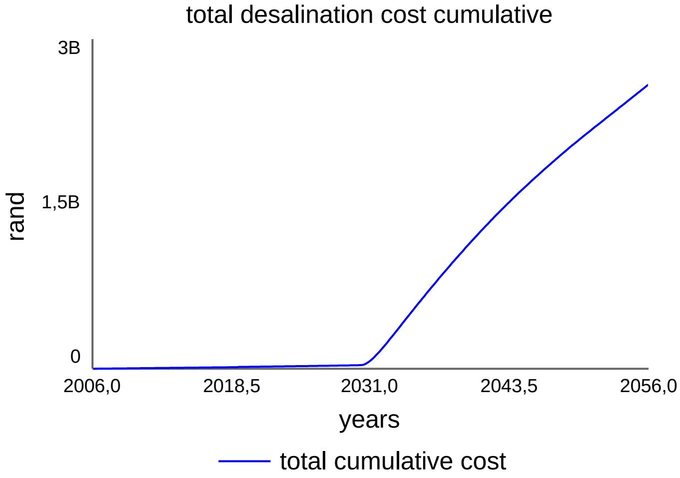


Figure 5D: total cost of desalination for implementation in 2030 (Agulhas)

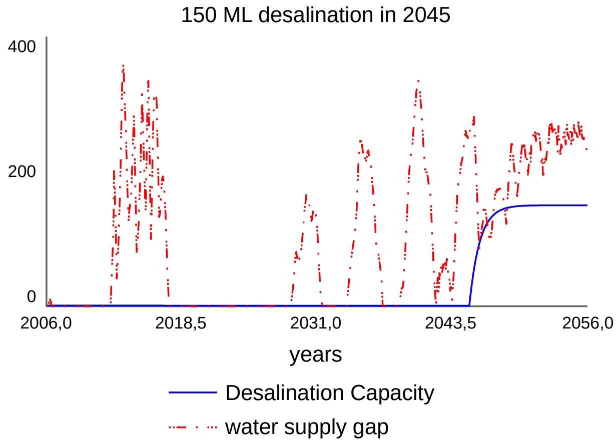


Figure 5E: water gap and desalination for implementation in 2045 (accounting for all other proposed augmentation intervention)

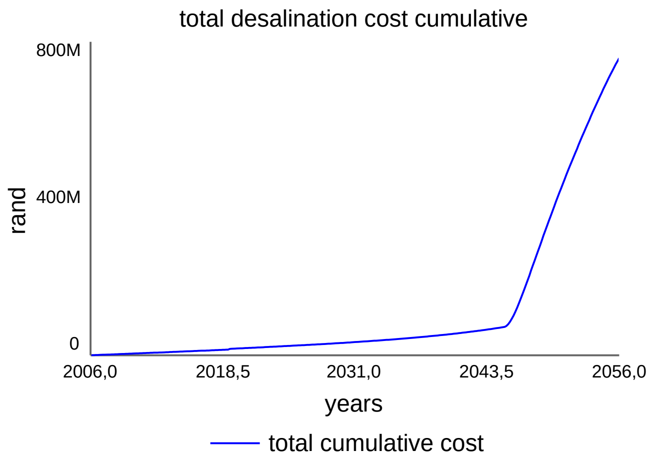


Figure 5F: total cost of desalination for implementation in 2045 (Agulhas)

<u>Decision point 4: Government tariffs on desalinated water</u>

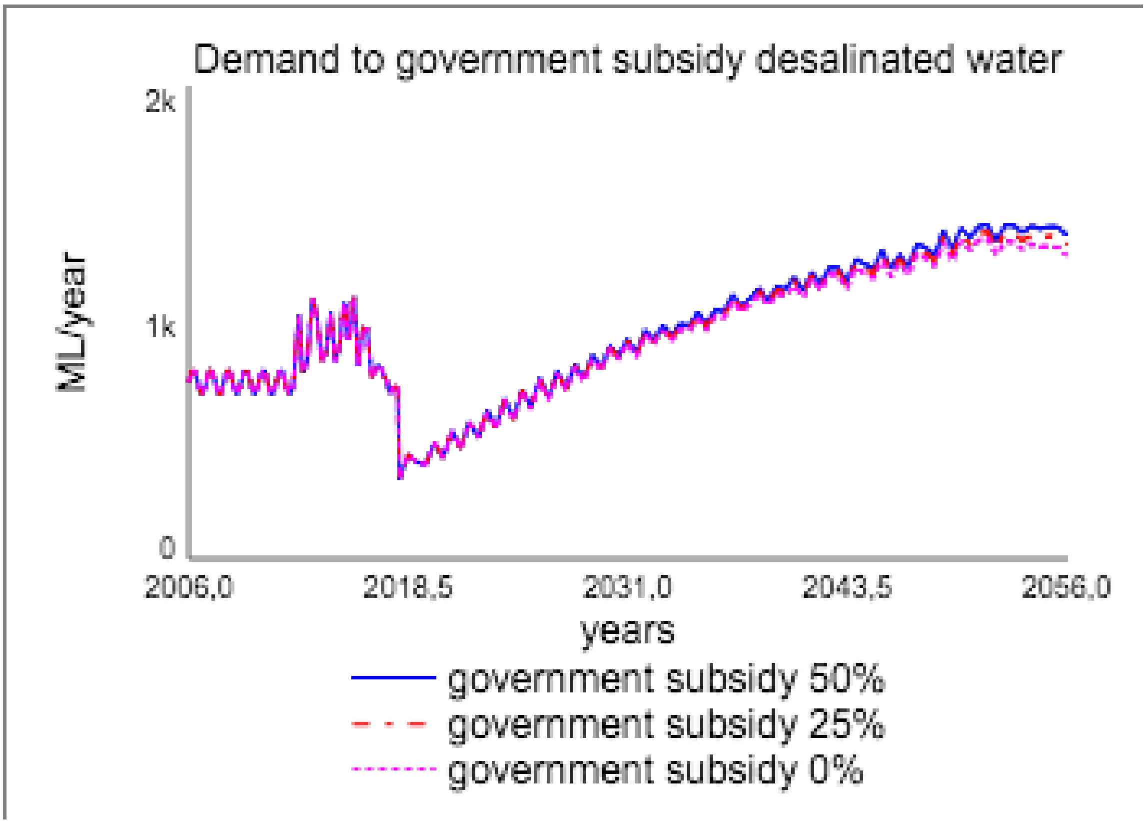


Figure 6A. government tariffs reflecting on demand

Decision point 5: Fish / Coal Pricing

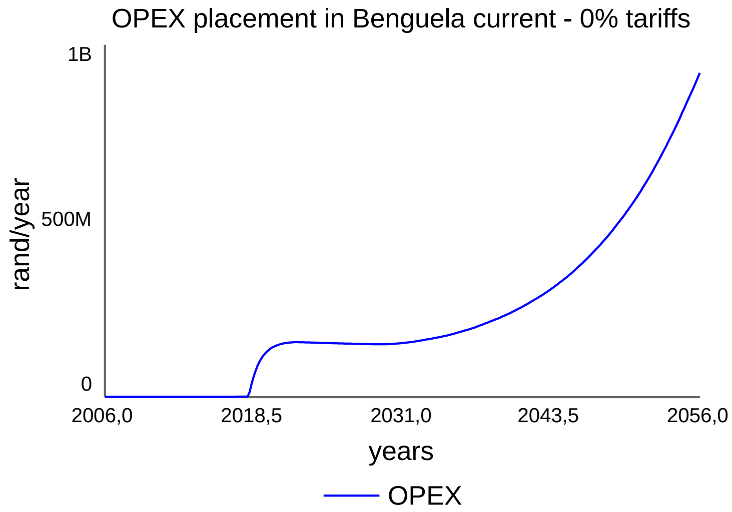


Figure 7A. OPEX for placement in the Benguela current, no subsidies on price

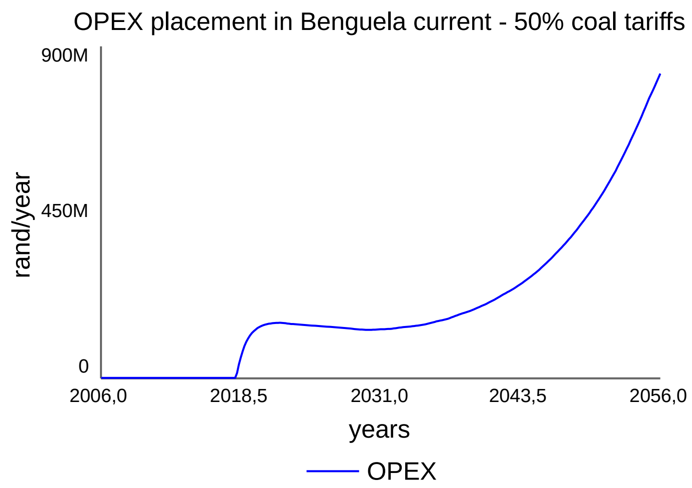


Figure 7A. OPEX for placement in the Benguela current, 50% subsidies on energy

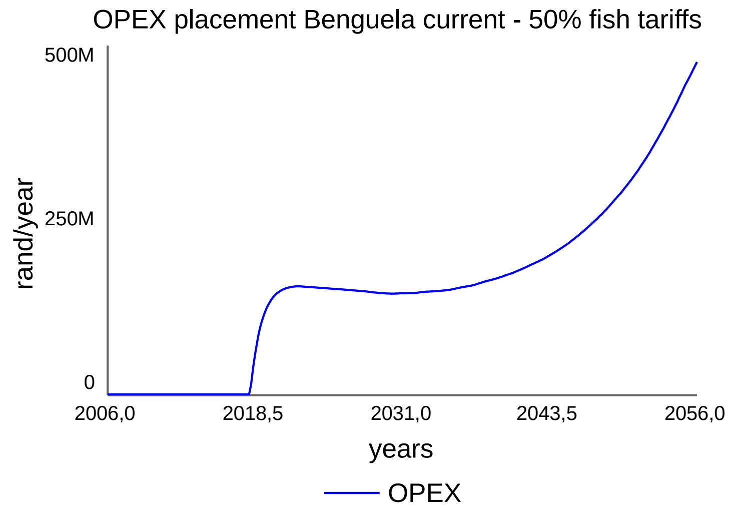


Figure 7A. OPEX for placement in the Benguela current, 50% subsidies on fish

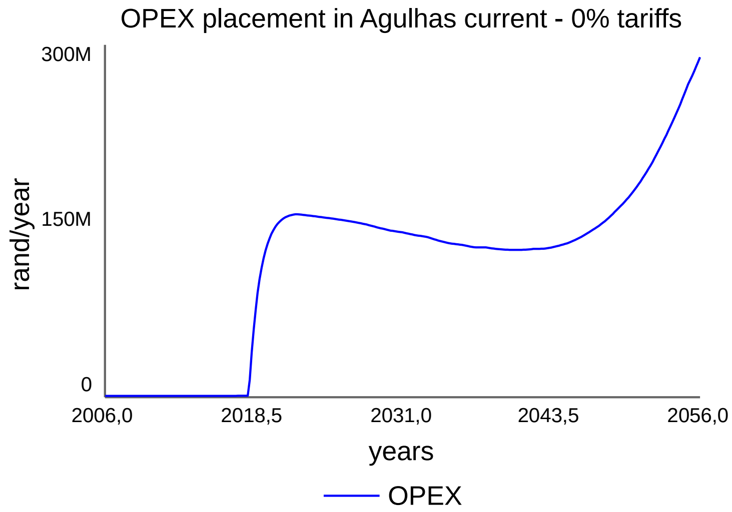


Figure 7A. OPEX for placement in the Agulhas current, no subsidies on price

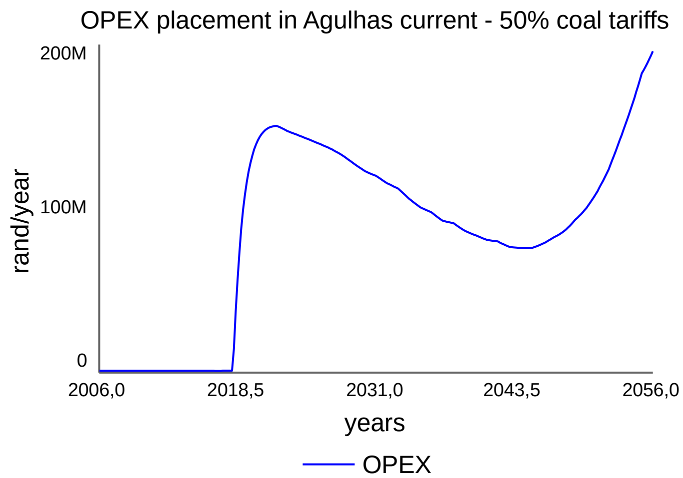


Figure 7A. OPEX for placement in the Agulhas current, 50% subsidies on energy

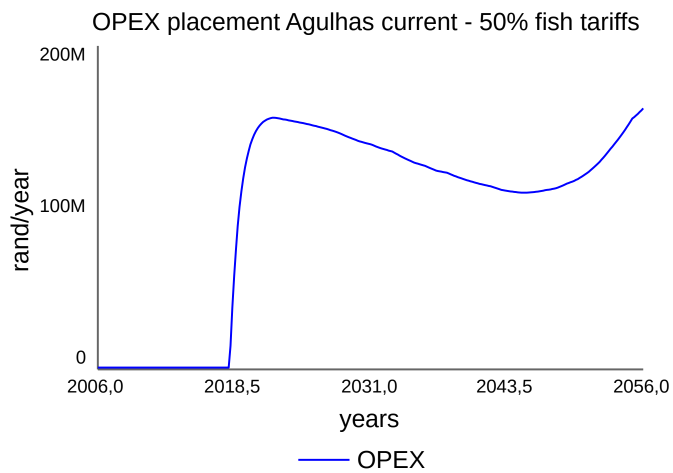


Figure 7A. OPEX for placement in the Agulhas current, 50% subsidies on fish

Annex X. Decision tree and argumentation Kelly et al. 2013

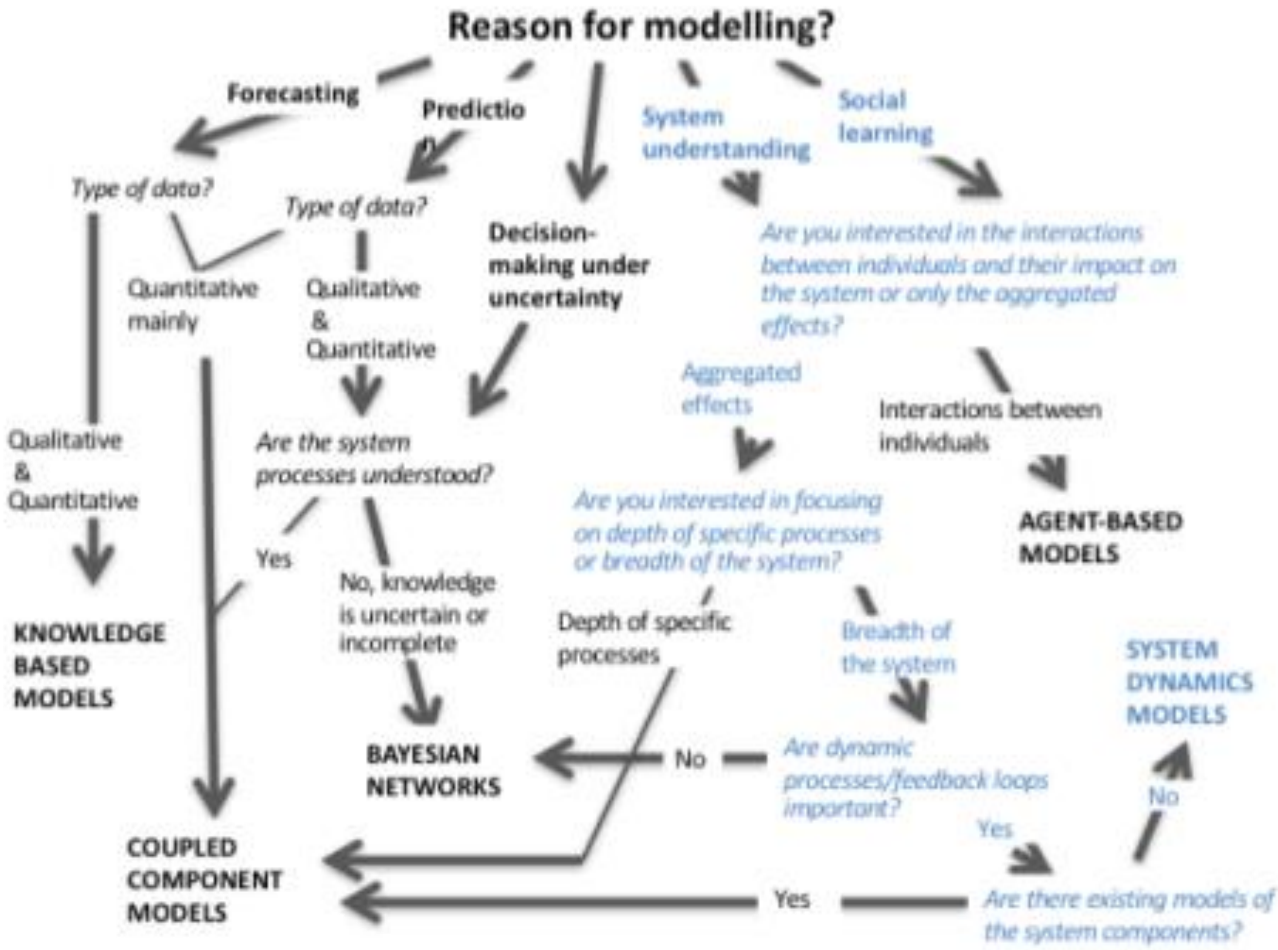


FIGURE 1. DECISION TREE OF THE CHOICE OF SYSTEM DYNAMICS (KELLY ET AL., 2013)

Appropriate use of integrated modelling approaches (X = common feature, * = possible feature).

		System dynamics	Bayesian networks	Coupled component models	Agent based models	Knowledge based models
Reason for modelling/type of application	Prediction	*	X	X	*	X
	Forecasting			X		X
	Decision-making under uncertainty	*	X	*	*	X
	System understanding	X	X	X	X	
	Social learning	X	X		X	
Type of data available to populate model	Qualitative and quantitative data	*	X	*	*	X
	Quantitative data mainly	X		X	X	
Model focus on a complex description of specific processes or greater breath of coverage of interactions in system?	Depth of specific processes	*		X	X	X
	Breadth of system	X	X	X	*	X
Model to provide explicit information about uncertainty caused by model assumptions?	Yes		X			
	No	X		X	X	X
Interest in investigating the interactions between individuals and their impact on the system, or only the aggregated effects behaviour?	Interactions between individuals				X	
	Aggregated effects	X	X	X	*	X

FIGURE 2. COMPARISON OF MODELLING METHODS (KELLY ET AL., 2013)